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CUMBERLANDIAN MOLLUSK CONSERVATION PROGRAM...

ACTIVITY 5:...
Analysis of Physical Habitat

Office of Natural Resources and Economic Development
Tennessee Valley Authority
Knoxville, Tennessee 37902

TVA/ONRED/AWR-86/13

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Tennessee Valley Authority
Office of Natural Resources and Economic Development
Division of Air and Water Resources
Engineering Laboratory

CUMBERLANDIAN MOLLUSK CONSERVATION PROGRAM

ACTIVITY 5:

ANALYSIS OF PHYSICAL HABITAT

Report No. WR28-1-80-102

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ABSTRACT

Activity 5 of the Cumberlandian Mollusk Conservation Program (CMCP) evaluated physical conditions at 15 study reaches in the Tennessee River Valley. This was part of a multiphase project to study several environmental factors as they relate to freshwater mussels. For the physical habitat characterization (conducted under Task I), areas of the Buffalo and Clinch Rivers, Copper Creek, and the Duck, Elk, Nolichucky, North Fork Holston, Paint Rock, and Powell Rivers were surveyed and measured to determine physical, hydrologic, hydraulic, substrate, and suspended sediment conditions. Data collected over a two-year period are summarized and presented in graphic and tabular form to facilitate the classification of river reaches according to habitat suitability for the endangered mussels.

Task II of CMCP Activity 5 studied the effect of instream structures (low-head dams) on the nature and stability of the downstream substrates. This task was conducted to determine if these dams alter the downstream physical environment to provide favorable conditions for mussel survival.

SUMMARY

The results from Task I showed that most site characteristics are related by the general size and topography of the reach of river studied. The relatively large reaches are Kyles Ford and Fort Blackmore (Clinch), Sowell Ford and Lillard Mill (Duck), Elk, and Hale Bridge (Nolichucky). The relatively small reaches are Copper Creek, Dement Bridge (Duck), Saltville (North Fork Holston), and Estill Fork (Paint Rock).

Special concerns at some of the reaches include potential washout during floods at Topsy Bridge (Buffalo) and low flows at Estill Fork (Paint Rock). High suspended sediment was measured at Kyles Ford and Fort Blackmore (Clinch), in the Elk, at Hale Bridge (Nolichucky), and at Buchanan Ford and Fletcher Ford (Powell). The results at the Elk River are less conclusive due to the lack of data at this site.

Task II, field reconnaissance of several mill dams, showed increased river width did not continue very far downstream of the mill structure. Most of the downstream flow still occurred in what appeared to be the original river channel.

A two-dimensional (vertically-averaged) mathematical computer model was used to study the river reach downstream of the Lillard Mill Dam on the Duck River. Modeling results show the main effect of the mill dam is the constriction caused by the old powerhouse, which affects the lateral distribution of flow in the river. The channelization of flow on one side of the river causes those areas with higher velocities to be swept clean of sediments, whereas sediment deposition occurs in the areas of low velocity. Under long-term average flow conditions, the modeling results show the large areas where mussel populations are found at the Lillard Mill reach are not affected by the lateral flow effects. The presence of the mussels in midchannel, where higher flow occurs, provides evidence that flow may be an important factor in potential hydraulic effects on mussel habitat.

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INTRODUCTION

The goal of the Cumberlandian Mollusk Conservation Program (CMCP) is to protect and enhance existing endangered Cumberlandian mussel populations. Identifying factors that are critical to the survival of these animals will assist in the development of programs to protect and increase species populations. An analysis of ecological conditions in 15 stream reaches has been conducted to identify sites that appear suitable for transplantation of the mussels. The study reaches are located on the Buffalo, Clinch, Duck, Elk, Nolichucky, North Fork Holston, Paint Rock, and Powell Rivers, and Copper Creek, a tributary to the Clinch River.

Ecological parameters studied for the CMCP include physical and hydrologic characteristics, water quality, benthic flora, plankton, and macrofauna. The purpose of Task I of Activity 5 (Physical Habitat Characterizations) is to provide study reach descriptions, including hydrologic characterization, streambed composition, and suspended sediment measurements. Task II of Activity 5 (Instream Structures Analysis) studies the effects of instream structures on downstream habitats.

The main emphasis of Task I of Activity 5 is comparison of the physical aspects of each study reach. Data for this task were accumulated over a period of approximately two years. The study reaches were surveyed, and bottom topography, preliminary determinations of streambed composition, and sampling grids were mapped to provide a basis for subsequent sampling. Velocities, depths, suspended sediment, and streambed measurements were taken to provide details on each reach. Task I includes a description of the methods used in arriving at physical characterizations. A description of each study reach is given to provide information on surrounding topography and land use, streambed topography, velocity distributions under a variety of flow conditions, and the surface and subsurface substrates. All the data available about the site, including long-term hydrologic characterizations and the results of

suspended sediment sampling, are then summarized to compare various aspects of each reach.

Task II of Activity 5 studies the effects of instream structures (mill dams or other low, man-made instream structures) on the downstream physical environment, especially the nature and stability of the downstream substrate. The impetus for studying low-head dam effects on downstream conditions was the presence of the Lillard Mill Dam just upstream of a large population of endangered mussels in the Duck River. A literature search on small dam effects was conducted to find any previous work on this subject. Several low-head dams other than at Lillard Mill were examined in an attempt to identify characteristic effects on the downstream reaches. Finally, a detailed study of the Lillard Mill site included field investigations and mapping, historical aerial photograph analysis, and modeling of the immediate environment with and without the dam in place.

TASK I - PHYSICAL HABITAT CHARACTERIZATIONS

The emphasis of Task I of Activity 5 was the comparison of the physical aspects of each study reach. A literature review showed few examples of specific analyses that cover the breadth of the Task I study. However, most sources agreed that an attempt to describe an aquatic habitat should identify significant basin characteristics such as river width, depth, substrate composition, flow volume, stream gradient, and drainage area. Principal sources regarding habitat characterization include Hynes (1970), Huet (1949), Herricks, et al. (1980), and Van Deusen (1954). The methods used to characterize each of the study reaches are presented to provide a basis for the later discussions.

TASK I METHODS

Physical Characteristics

Each study reach was chosen to be 600 to 650 feet in length in a relatively straight river segment. A baseline was established on the

most convenient side of the river. In addition, a reference line parallel to the stream centerline was established so that all transverse measurements were made perpendicular to the stream centerline. If the reach was straight, the baseline served as the reference line. Temporary markers for use by the sampling crews were positioned on the base and reference lines at 50-foot intervals. The baseline origin (designated station 0+00) was located at the downstream end of the reach. Reference to right or left banks was determined from the view facing downstream.

Physical characteristics studied in this analysis include geographic location, topography, surrounding land use, drainage area, and stream widths, depths, and gradients. Topographic quadrangle maps were used to establish geographic location, general area topography, surrounding land use, and drainage area. Stream profiles were used for stream gradient determinations, supplemented by water surface slopes and topographic quadrangle maps. Direct observations were used to determine site topography, including stream widths and depths and specific land use.

Hydrologic Characteristics

A staff gage for establishing river elevations and flow conditions was located at each study reach except at Saltville (North Fork Holston) where there is a long-term stage gage just downstream of the reach. Elevation, latitude, and longitude were determined for each staff gage.

Considerable effort was made to determine site-specific hydrologic information. Field measurements were taken at each study reach to determine stage-discharge relationships and velocity distributions throughout the reach. The field discharge data were also used to estimate physical size information (width and depths) under average and low flow conditions, and to estimate suspended sediment loadings.

Hydrologic summary information was obtained from long-term data taken at nearby stream gages, as reported by the U.S. Geological Survey. Information on flow duration and representative low, average, and high

flows were all obtained from these records, adjusted by using drainage area ratios. The streamflow data were supplemented by records from nearby similar watersheds for flood determinations.

At each study reach three cross sections were selected to characterize velocity and sediment information. An effort was made to obtain at least five sets of field measurements at each site, covering a range of flows. One of the three cross sections was used to determine discharge corresponding to the observed river stage.

Vertical velocity distributions at several lateral points in each of the three cross sections, total discharge, and river stage (height) were recorded for each sampling period. Velocities were measured using a Price meter, type AA. Distances were measured using a steel tape. The mid-section method for computing cross-sectional area was used with the velocity-area method to determine river discharge (U.S. Department of the Interior, 1977). Velocity distributions and mean velocities were measured at the six-tenths depth, or using the two-point method (0.2 and 0 8 of depth), or three-point method (0.2, 0.6, and 0.8 of depth) depending on the depth at the sample point (U.S. Department of the Interior, 1977).

The velocity measurement results are presented, using the lowest and highest velocities measured near the streambed. Each velocity figure provides the lowest velocities at the actual measured cross section while the highest velocities are offset (actual cross sections were the same). Average cross section velocities were calculated by dividing the measured discharge by the measured cross-sectional area. Regression analysis was used to fit the discharge and velocity data at each cross section to a second order curve passing through the origin. The velocity at the long-term average discharge was then determined from the regression curve. The resulting velocities at each of the three measured cross sections were then averaged to determine the average velocity in the study reach under average flow conditions. These average velocities at average flows were used for study reach comparisons.

Streambed Composition

Samples of the substrate were collected during the mussel sampling surveys carried out under Activity 8, Macrofauna Analysis, to provide directly comparable information on mussel substrate preferences. Sampling was done during low flow conditions and should have revealed any fine materials normally present in the study reaches. The surveys used a stratified random sampling technique with locations for samples chosen by a computer random number generating program. Details of the technique are given in the Activity 8 report.

Substrate was collected at the surface and at approximately the 3-inch depth at each randomly selected sampling location. Each hand sample was characterized by the following particle size categories:

F = silt or clay (fines)

S = sand

G = gravel up to 3 inches

C = cobble 3 inches to 1.5 feet

R = boulders or bedrock greater than 1.5 feet

This terminology is used in the presentation of sampling results for each site. The substrate point data were supplemented by the preliminary streambed composition maps that were made during the site surveys.

Suspended Sediment Concentration

Suspended sediment measurements were taken in conjunction with the velocity measurements described previously. Depth-integrated samples were collected using a US D-49 depth-integrating sampler developed by the Federal Interagency Sedimentation Project, sponsored by the U.S. Water Resources Council (U.S. Interagency Report, 1963). Samples were collected at five lateral locations in each of the three study cross sections and analyzed by TVA's Singleton Materials Engineering Lab in Louisville, Tennessee. The resulting concentrations (in parts per million by weight) were plotted according to lateral distance on cross section graphs to identify any trend in the lateral distribution of suspended sediment.

A mean discharge-weighted (depth and lateral average) concentration was calculated for each cross section using the measured

discharge information. Each depth-integrated concentration was multiplied by the representative discharge in the river subsection, totaled, and divided by the total cross section discharge. This method is a slight variation of the equal-discharge increment (EDI) method (U.S. Department of the Interior, 1977) which allows for variable discharge subsections.

Suspended sediment concentration measurements were also taken as part of Activity 6, Analysis of Water Quality. These mid-channel samples provided supplemental data that were helpful in characterizing suspended sediment concentrations under low flow conditions. The laboratory analyses of these samples were conducted by TVA's Laboratory Branch in Chattanooga, Tennessee, using the same standard method as used at the Singleton Lab.

The mean discharge-weighted suspended sediment concentrations for each cross section measurement (Activity 5) and mid-channel samples (Activity 6) were converted to sediment discharge in tons per day using the cross section discharge and the appropriate unit conversion factors. Estimated sediment discharge ratings were made from the sediment discharge versus river discharge results using a log-log linear regression of the sample points. Suspended sediment concentrations at average flow conditions were obtained from these ratings using the long-term average discharge. Long-term flow frequency (duration) curves were then used with the sediment discharge ratings to approximate the average annual sediment yield (American Society of Civil Engineers, 1975).

TASK I STUDY REACH DESCRIPTIONS

Figure 1 shows the 15 study locations within the Tennessee River Basin. Table 1 provides a summary of geographic information about each of the sites. Seven sites are located in middle Tennessee and northern Alabama in the Interior Low Plateau or Appalachian (Paint Rock) Physiographic Provinces. The Highland Rim section of this province is characterized by a residual blanket composed primarily of clay, chert

Table 1. General geographic information on CMCP study reaches.

CMCP Reach	River	State	River Mile	Latitude	Longitude	General Area in Tennessee River Watersned
Topsy Bridge	Buffalo	TN	79.9	35°26'16"	87°42'26"	West
Kyles Ford	Clinch	TN	189.5	36°34'10"	83°02'29"	East
Fort Blackmore	Clinch	VA	227.4	36°45'57"	82°34'58"	East
Copper Creek	Copper Creek	VA	1.9	36°39'24"	82°43'06"	East
Sowell Ford	Duck	TN	159.4	35°35'34"	86°53'02"	West
Lillard Mill	Duck	TN	179.1	35°35'12"	86°47'04"	West
Halls Mill	Duck	TN	202.2	35°33'15"	86°35'02"	West
Dement Bridge	Duck	TN	243.1	35°28'00"	86°17'41"	West
Elk	Elk	TN	91.4	35°07'30"	86°33'48"	West
Hale Bridge	Nolichucky	TN	27.8	36°05'48"	83°03'03"	East
Click Island	N. Fork Holston	VA	6.2	36°35'53"	82°35'36"	East
Saltville	N. Fork Holston	VA	85.2	36°54'01"	81°44'47"	East
Estill Fork	Paint Rock	AL	60.0	34°53'49"	86°10'16"	West
Buchanan Ford	Powell	TN	99.2	36°33'30"	83°25'24"	East
Fletcher Ford	Powell	VA	117.4	36°36'10"	83°17'34"	East

blocks and fragments, siliceous silt, and some sand, generally 30 feet or more in thickness. Portions of the Nashville (Central) Basin section are underlain in limestone formations of varying purity. Some of the uppermost limestone formations are thin bedded with the beds separated by thin layers of clay shale.

The remaining eight study reaches are located in northeast Tennessee or southwest Virginia in the Valley and Ridge Province bordering the Southern Appalachian Mountain Range. This area is characterized by northeast-trending parallel valleys and ridges. It is underlain by carbonate rock formations such as limestone and dolomite together with calcareous shale and limey sandstone.

The following physical description of each study reach along with the hydrologic characteristics, streambed composition, and suspended sediment measurements provides an introduction to each site. The classification results will be summarized in later sections of the report which provide site comparisons.

Topsy Bridge, Buffalo River

The Buffalo River is a major tributary to the Duck River in the Interior Low Plateau Physiographic Province. The Topsy Bridge study reach (Figure 2) is located at Buffalo River Mile 79.9 near Topsy, Tennessee, in the central section of the state (Quadrangle Map 42 NW, Topsy, Tennessee). The site drains approximately 342 square miles of watershed which is heavily used for agriculture. The Buffalo River originates in Lawrence County near Summertown and meanders through gently rolling hillside terrain to its confluence with the Duck River near the point where the Duck empties into the Tennessee River (TRM 110.7). There are no major flow control structures upstream of this site.

The study reach is located downstream of a large (greater than 90°) left bend in the river. The river banks are very steep before entering a flatter floodplain on the right bank near the downstream end of the site. The left bank has forests up to the water's edge; the

upstream right bank is a bluff. The stream bottom topography is variable, with deeper areas located near the right bank because of the upstream bend (Figure 3). A large rock is located near the right bank at station 5+50 (550 feet from baseline origin, station 0+00).

Figure 4 provides the measured low and high velocity distributions at Topsy Bridge. The highest velocities were measured to the right of mid-channel in deep water. A large rock in the upstream portion of the reach near the right bank essentially blocks flow, particularly under low flow conditions. Both the station 4+00 and station 5+50 measurements show a double hump distribution due to shallow mid-channel areas.

Random sample results of the surface substrate at Topsy Bridge showed a variable distribution except for the lack of large-sized rock. Figure 5 shows that silt/clay substrate was found primarily near the left bank, where the stream is shallow and flow velocities are low. Sandy material was found on the mid-channel side of the silt/clay, with the area from mid-channel to the right bank mostly gravel and cobble. An area of silt/clay was also found in a deep region on the right bank between station 4+00 and station 5+00, where a large rock causing low velocities prevents the finer material from being washed away.

The subsurface substrate (3-inch depth) also had a variety of particle sizes. Some specific areas were identified, such as rock in the deep areas on the right bank under the silt/clay, cobble in the upstream end, and gravel at the downstream end of the reach. The rest of the material was fairly well mixed.

Kyles Ford, Clinch River

The Clinch River flows through the Valley and Ridge Physiographic Province from its origin in southwest Virginia to its confluence with the Tennessee River near Kingston, Tennessee. Norris Dam, located at Clinch River Mile (CRM) 80, floods approximately 70 miles of the river well below the study sites. There are a few small towns, farms, industrial plants, and coal mines along the river in the mountainous area above the impoundment.

The study reach at Kyles Ford, CRM 189.5, is shown in Figure 6 which is taken from the Kyles Ford, Tennessee-Virginia, Quadrangle Map 170 SE. The town of Kyles Ford is located approximately one-half mile upstream of the study site. The stretch of river through the reach is of nearly uniform width, with a steep, wooded right bank and rolling farmland on the left. The drainage area to this point on the Clinch is approximately 1,126 square miles.

Figure 7 provides the bottom topography at the site. Because of a sharp bend in the river just above the reach, higher velocities tend to be on the right bank, resulting in the deposition of sediment and the buildup of a wide floodplain on the left. There are several rocky shoals in the reach that are dry under low flow conditions. Figure 8 illustrates the low and high measured velocity distributions at the site.

The surface substrate composition at Kyles Ford is somewhat variable, as shown in Figure 9, but follows patterns consistent with the prevailing flow conditions. The smaller-sized clay/silt material was all found in the shallow areas associated with low velocities. Rock was found mainly near mid-channel with gravel nearer the banks. High mid-channel flows wash the rock clean and deposit gravel nearer the banks where the velocity can no longer support the particles. Sand was found scattered throughout the reach.

The subsurface substrate had almost no silt/clay or cobble. Rock was found primarily in mid-channel in the upstream end of the reach and near the right bank at the lower end. The sand and gravel were scattered throughout.

Fort Blackmore, Clinch River

The description of the Clinch River given in the previous section also applies for this site. The Fort Blackmore study reach is located just upstream of the bridge leading to the city of Fort Blackmore at CRM 227.4. The drainage area for this site is 897 square miles. Figure 10 (from the Fort Blackmore, Virginia, Quadrangle Map 187 SE) shows the general topography of the area. There is a wide

floodplain on the right bank of the river with a sheer bluff on the left bank. The lower half of an island extends downstream approximately 400 feet into the reach, creating a narrow channel along the right bank. Only the wider channel toward the left bank was sampled during this project.

Figure 11 provides the bottom topography of the site. The site is characterized by a long, rocky, riffle area which is fairly shallow in the downstream end of the reach. The upstream channel is deeper near the left bank.

The velocity distribution at Fort Blackmore is correlated with the topography in the reach, i.e., higher velocities are found in the deeper areas near the left bank (Figure 12). The bridge piers at the lower end of the reach cause flow to break from its normal open-channel distribution.

The streambed at Fort Blackmore (Figure 13) is composed of cobble and rock at the surface. The subsurface substrate was found to be predominantly gravel. The lack of small-sized material can be attributed to the steep river slope in this reach and associated high velocities.

Copper Creek

Copper Creek is a tributary to the Clinch River, located in southwestern Virginia in the Valley and Ridge Physiographic Province (Figure 14 from the Clinchport, Virginia, Quadrangle Map 188 NW). The creek flows westward through high ridges from its source in the Moccasin and Copper Ridges in Russell County, draining approximately 131 square miles at the site. The creek is sparsely populated along its banks. The study reach is located at Copper Creek Mile 1.9 just upstream of the mouth of the creek near Spears Ferry, Virginia (CRM 211.6). A bridge is located at the downstream edge of this site.

The study reach at Copper Creek is very straight after a right bend which occurs upstream of the site. This bend is probably the cause of a slight deviation in flow in the upstream end of the reach. Figure 15 shows little variation in depth over the narrow reach.

The low and high measured velocity distributions at the site are shown in Figure 16. The left bank areas are a little deeper and show slightly higher velocities until station 2+00 where the right bank is deeper.

The substrate at Copper Creek is gravel and cobble at the surface, underlain with sand (Figure 17). Silt/clay was found near the banks. The streambed has a steep slope which accounts for the predominance of larger-sized particles at the surface.

Sowell Ford, Duck River

The Duck River originates in Coffee County, Tennessee, and flows westward for about 290 miles before emptying into Kentucky Reservoir at Tennessee River Mile 110.7. All of the study reaches on the Duck River are in the Nashville Basin Section of the Interior Low Plateau Physiographic Province. The region through which the Duck River flows is generally low in relief with some rolling hillsides. Land use is mostly agriculture and forest. Since the completion of Normandy Dam in 1976, the headwaters of the Duck River have been impounded above Duck River Mile 248.

The location of Sowell Ford study reach, Duck River Mile 159.4, is shown in Figure 18 (from the Glendale, Tennessee, Quadrangle Map 64 SW). The topography at Sowell Ford is, generally, rolling terrain with a steeper slope on the right bank. Figure 19 provides more detail of the site showing the shallow regions near the left bank. The remains of an old crib dam are found on the left bank at the upstream edge of the reach. The river is relatively straight just before the study reach, and dense foliage borders both river banks. The drainage area is approximately 1,025 square miles.

Velocities at the left edge of the water at the Sowell Ford site vary considerably due to extensive shallow areas. Under high flow conditions this section is flooded, with lower velocities than the deeper areas (Figure 20). A dip in bed topography toward the left bank at station 5+75, however, causes slightly higher currents. A rise in

the bed topography at station 3+50 in mid-channel divides the flow into two channels during low flow conditions.

The surface streambed composition at Sowell Ford (Figure 21) shows a variable distribution of material sizes except for sand. Most of the silt/clay substrate was found near the banks, especially on the left side of the reach, where low velocities were measured. The left bank area is very shallow and normally dry under most flow conditions. During high flows the area is flooded, but velocities are not large enough to wash the area clean of silt/clay. Closer to the right bank flows are normally higher and the area is mostly composed of clean rock and gravel.

The subsurface substrate material is predominantly rock with some gravel and sand. The smaller-sized materials are found in the shallower areas.

Lillard Mill, Duck River

The Lillard Mill site is located at Duck River Mile 179.1 just downstream of the old mill dam. The site drains an area of approximately 916 square miles. Figure 22 shows the general low relief near the site (from Verona, Tennessee, Quadrangle Map 64 SE). The banks of the reach are covered with dense weeds and trees. Several gravel islands cause the study reach to be braided in character. Figure 23 shows the general bed topography.

High flow at Lillard Mill shows a velocity distribution broken up by the shallow areas that become islands under low flow conditions (Figure 24). The old mill dam powerhouse just upstream of the reach influences flow and substrate by constricting the river, causing higher velocities on the left side of the river. However, the flow patterns in the study reach itself (approximately 450 feet downstream (see Task 2) of the dam) are near what would be expected.

The surface substrate at Lillard Mill is quite variable with silt/clay material near the banks and a mixture of gravel, cobble, and rock near mid-channel (Figure 25). Rocky material predominates on the

left side of the island at station 4+50 where high velocities keep the deeper areas washed clean of fine material. Lower velocities near the banks allow silt/clay to accumulate.

The subsurface is again quite varied with silt/clay near the banks. The other size categories appear grouped in small areas. Rock is found in the shallower areas.

Halls Mill, Duck River

The Halls Mill study reach is located at Duck River Mile 202.2, downstream of the Halls Mill Bridge and the remnants of an old mill dam. The drainage area at the site is 481 square miles. Figure 26 is taken from the Unionville, Tennessee, Quadrangle Map 71 SE. The river banks at the site vary from gently sloping at the upstream end of the reach to steep, rocky bluffs near the lower end. An island and peninsula, shown in Figure 27, give the reach a braided character similar to that found at Lillard Mill.

Measured velocities at the Halls Mill site are shown in Figure 28. The island divides the flow during low and average flow conditions. At high flows a shallow peninsula at station 5+50 directs flow toward the right bank.

At the Halls Mill site the surface substrate (Figure 29) is composed mostly of rock with clay/silt material predominating on the left bank. Higher flows tend to occur near the right bank keeping that area free of fine material. The subsurface substrate is mainly rock throughout the reach with some gravel near the edges of the river.

Dement Bridge, Duck River

The Dement Bridge study reach is located about five miles downstream of Normandy Dam at Duck River Mile 243.1. Normandy Dam has a minimum flow requirement of 40 cubic feet per second (cfs) but also operates to maintain a flow of 155 cfs at Shelbyville, Tennessee, Duck River Mile 221.4. The terrain at the site is generally flat as shown in

Figure 30 (from the Normandy, Tennessee, Quadrangle Map 79 NE), with cultivated land on both sides of the reach. A line of trees separates the river from the farmland on both banks. The drainage area is about 221 square miles. Figure 31 shows that the water depth in this reach is normally much shallower than the other Duck River sites. The reach is just below a road bridge and has a small island near the upstream left bank. Under low flow a rocky riffle breaks up the flow in a cross section just downstream of the island.

The island near the left bank at the upstream end of the reach significantly affects velocities at the Dement Bridge reach (Figure 32). Velocities at station 6+00 appear slightly influenced by the bridge piers. Higher velocities were measured near the right bank in deeper areas.

The surface substrate at Dement Bridge is almost entirely gravel (Figure 33). Finer clay/silt and sand were found near the river banks during the preliminary substrate mapping but are not shown in the figure. The subsurface composition is mainly sand, unlike most of the other Duck River study reaches which have larger-sized subsurface materials.

Elk River

The Elk River is located in south-central Tennessee and flows from Grundy County generally westward until it reaches Wheeler Reservoir on the Tennessee River. The study reach is at Elk River Mile 91.4 about two miles upstream of Fayetteville, Tennessee, with a drainage area of approximately 846 square miles. The site is located along the border of the Highland Rim and the Nashville (Central) Basin of the Interior Low Plateau Physiographic Province. There are two major dams located about 40 miles (Tims Ford) and 80 miles (Woods) upstream of the reach. Tims Ford Dam, the larger, at River Mile 133 is operated by TVA, providing flood control, water supply, and electric power. A river elevation requirement exists at the USGS stage gage in Fayetteville, resulting in a minimum flow of 144 cfs at this site. Tims Ford is normally operated

with a margin of safety providing flow near 175 cfs. The terrain near the study reach is generally flat as shown in Figure 34 (from the Fayetteville, Tennessee, 73 NE and Lincoln, Tennessee, 73 SE, Quadrangle Maps). Cultivated land extends to the right bank; the left bank is next to a low bluff.

Figure 35 provides a detailed map of the study reach showing a small island near the right bank and a stream coming into the site near the downstream end. The streambed is shallower near the left bank throughout the reach because of higher velocity near the right bank resulting from the bend above the reach. A particularly shallow area occurs on the left bank at station 0+00. Figure 36 shows the low and high velocity distributions measured at the site.

Site substrate sampling shows predominantly cobble and gravel in the surface layer near mid-channel with silt/clay near the banks (Figure 37). The subsurface material sampled was mostly sand and gravel, with silt/clay near the banks.

Hale Bridge, Nolichucky River

The Nolichucky River originates in Mitchell County, North Carolina, and flows southwestward through mountainous terrain to its confluence with the French Broad River in Douglas Reservoir.

The Nolichucky Dam at Nolichucky River Mile 46.0 was strengthened and rehabilitated by TVA in 1973 and is now operated in conjunction with a waterfowl management program. At the time the dam was renovated, siltation was a major problem in Davy Crockett Lake. Since the renovation project the gate has been closed and there is no meaningful control of flows at the dam.

The Hale Bridge study site is located in the Valley and Ridge Province approximately 18 miles downstream from Nolichucky Dam at River Mile 27.8. Figure 38 shows topography of the area (from the Parrottsville, Tennessee, Quadrangle Map 172 SE). Bewley Island divides the river into two channels near the site, and the left channel is further divided by a smaller, unnamed island. The drainage area at the site is approximately 1,289 square miles.

Figure 39 shows more detail of the site with the small island forming the right bank of the reach. The shallow area that starts upstream of the reach (see dry area in Figure 39) causes velocities to be higher in the small "channels" between the shallow and the island bank (Figure 40). Higher velocities also appear at the left bank in the upstream area. At the downstream edge of the reach the bed topography is more uniform with normal velocity distributions (i.e., higher in mid-channel, lower near the banks). There are rocky shoals located downstream of this area.

The preliminary streambed mapping and random sampling show silt/clay with cobble and gravel in the mid-channel areas with only silt/clay and gravel at the banks (Figure 41). Rocky material is not found at the surface but is prevalent in the subsurface, especially in the downstream end. The remaining subsurface areas show a random distribution of materials.

Click Island, North Fork Holston River

The headwaters of the North Fork of the Holston River begin north of the town of Saltville, Virginia, in the Valley and Ridge Province. The river flows southwest to its junction with the Holston River near Kingsport, Tennessee. Along the length of the river, the area is generally hilly with deep valleys, heavily wooded, with occasional mines and quarries. Numerous creeks empty into the river. There are no major flow obstructions on the river.

The Click Island study reach at River Mile 6.2 is shown in Figure 42 (from the Kingsport, Tennessee-Virginia, Quadrangle Map 188 SE). Click Island extends from the upper end of the reach at station 6+00 to station 3+50, creating a channel along the left bank which occasionally goes dry. Very shallow areas near the tip of the island also dry up as shown in Figure 43. A line of rapids stretches across the river between stations 3+50 and 2+00. The right bank slopes steeply to the water, with dense foliage growing down to the water's edge. The left bank is cultivated farm land. The drainage area at the Click Island site is 688 square miles.

The river just downstream of Click Island (station 3+00) is quite shallow with rocky shoals causing low velocities at several points in the cross section (Figure 44). Even under high flows the rocky areas affect flow.

Surface substrate at Click Island was found to be quite variable. Figure 45 shows the regions where specific size categories were found. Lower flows in the area toward the left bank from the island cause the clay/silt to remain in that location. The subsurface composition is also quite varied with silt/clay the only small size material found in significant quantity.

Saltville, North Fork Holston River

The Saltville study site is located within a relatively wide valley with farmland adjacent to the river on both banks. The reach is very close to the city of Saltville, Virginia, at River Mile 85.2 as shown in Figure 46 (from the Broadford, Virginia, 218 NW, and Saltville, Virginia, 212 NE, Quadrangle Maps). The drainage area for this site is 222 square miles. Figure 47 shows an island that divides the river in this reach with only the left channel remaining wet during periods of low flow. The water surface at the downstream end of the site (below station 3+00) is broken in several places by rocky shoals and riffles.

Velocities at the Saltville site were measured only on the left side of the island (Figure 48). Under low flow conditions the velocities are essentially zero near the right bank at the upstream edge of the reach. Under high flows the velocities are high across the entire section. The edges of the channel in the downstream portion of the reach are slightly deeper than at mid-channel causing velocities to be slightly higher at times than would normally be measured near the banks.

The randomly sampled surface substrate at Saltville is predominantly rock underlain with a mixture of silt/clay, sand, and gravel (Figure 49). Silt/clay in the subsurface sampling is located near the upstream end of the site. The river slope at Saltville is the steepest of any of the study sites, accounting for the high velocities which wash out the fine material leaving a predominately rocky surface.

Estill Fork, Paint Rock River

The Paint Rock River is formed by the junction of Estill Fork and Hurricane Creek near the town of Estill Fork, Alabama, from where it flows 60 miles south-southwest to empty into the Tennessee River at Tennessee River Mile 343. There are no dams or other flow obstructions on the Paint Rock.

The confluence of Hurricane Creek and Estill Fork form the upstream end of the study reach as shown in Figure 50 (from the Estill Fork, Alabama, Quadrangle Map 88 NW). The watersheds for both Estill Fork and Hurricane Creek are heavily forested, with a drainage area at the site of 99.5 square miles. There is a 50- to 75-foot area of overbank on the left side of the reach with a farm located very close to the river on the right bank. The gravel island located in the middle of the reach dominates the area by channeling the current toward the right bank under low flow conditions. Areas toward the left bank dry up during low flow as shown in Figure 51.

River velocities entering the Estill Fork reach are higher near the left bank as a result of the higher flow from Hurricane Creek (Figure 52). Areas toward the left bank of the island are dry during low flows, with the remaining flow channeled toward the right bank.

Estill Fork has the largest amount of sandy surface substrate of any of the study reaches. Sand was found primarily in the area just downstream of the island and on the right bank in the upstream portion of the reach, as shown in Figure 53. The higher velocities in the upstream portion of the reach near the left bank keep this area washed of finer material. Since flow is channeled to the right side of the island, the substrate in that area also was found to be free of silt/clay and sand.

The subsurface substrate contains gravel in samples taken downstream of the island. Upstream, the subsurface is mostly composed of sand.

Buchanan Ford, Powell River

The Powell River is a tributary to the Clinch, flowing southwest from Wise County, Virginia, to its confluence with the Clinch in Norris Reservoir at Clinch River Mile 89.0 in the Valley and Ridge Physiographic Province. The Powell River has a relatively narrow streambed with small towns, farms, industrial plants, and coal mines located along the banks. Significant coal mining in the area causes heavy suspended sediment loading, and deposits of coal fines were common in areas studied. There are no dams or other flow obstructions on the river. The terrain throughout the length of the river is generally hilly.

The Buchanan Ford study reach is located at Powell River Mile 99.2 as shown in Figure 54 (from the Coleman Gap, Tennessee-Virginia, Quadrangle Map 161 SW). The area is mountainous with little floodplain in the study reach. An island extends through this site and only the right channel is shown in Figure 55. The reach is characterized by rocky shoals where a ford still exists. The drainage area is 540 square miles.

The study reach at Buchanan Ford is relatively straight with deeper areas near the left bank (island side). The velocity distributions shown in Figure 56 point out the slightly higher velocities in the deeper areas.

The substrate at Buchanan Ford is composed of cobble and sand underlain with gravel (Figure 57). The preliminary mapping of the substrate showed silt/clay among the larger particles, probably as a result of the heavy suspended sediment loads that are associated with the reach.

Fletcher Ford, Powell River

The Fletcher Ford site is located in an isolated section of southwest Virginia at Powell River Mile 117.4. The mountainous relief near the area is shown in the portion of the Back Valley, Tennessee-Virginia, Quadrangle Map 161 SE in Figure 58. At this point the river is relatively narrow with rocky shoals and heavy vegetation on

the floodplain. There are two general topographic regions at the Fletcher Ford site. The lower end of the reach is shallow (Figure 59), while deeper rocky shoals dominate the middle and upper end of the reach. Drainage area above this site is 464 square miles.

Flow enters the study reach through a narrow section which has a deep, swift current near the right bank caused by a bend in the river upstream of the study reach. At station 3+00 the site becomes very shallow with currents flowing around the sometimes-submerged island at station 0+00. Velocity distributions at the site are shown in Figure 60.

The surface substrate samples from the shallow area show mainly cobble with a much wider variety of material in the upstream area (Figure 61). Clay/silt is found near the river banks, especially in a shallow area near the left bank at station 5+00 and station 5+50. Sand-sized material is also found in numerous spots in the upstream reach.

In the downstream area the underlying substrate is almost exclusively gravel, while a mixture of material is found in the upstream end of the reach.

TASK I SUMMARY OF DATA

Physical Data

The 15 study reaches were chosen after preliminary consideration of several environmental factors as they relate to freshwater mussels. A decision was also made to restrict the study to the Duck River system and the Tennessee River system above Muscle Shoals, Alabama. Details of the selection process are documented in the Activity 9 report.

General physical characteristics for each study reach are shown in Table 2. With regard to relative size, the small river reaches (small drainage areas, depths, and widths) are Copper Creek, Saltville (North Fork Holston) and Estill Fork (Paint Rock). Dement Bridge (Duck) also has a small drainage area and depth although it is similar in width to some of the medium-sized reaches. Relatively large river reaches include Kyles Ford and Fort Blackmore (Clinch), Sowell Ford and Lillard Mill (Duck), Elk, and Hale Bridge (Nolichucky).

Table 2. Summary of physical data for CMCP study reaches.

CMCP Reach	River	RM	Drainage Area (mi^2)	Mean Depth* (ft)	Center Line Mean Depth (ft)†	Mean Width (ft)‡	Range of Widths (ft)		Stream Gradient (slope)	
							Low	High	(ft/mi)	(0/00)§
Topsy Bridge	Buffalo	79.9	342.0	3.8	4.1	119.0	82.0	144.0	3.4	0.64
Kyles Ford	Clinch	189.5	1268.0	2.9	5.5	287.0	244.0	300.0	2.0	0.38
Fort Blackmore	Clinch	227.4	897.0	2.5	2.1	222.0	130.0	334.0	6.4	1.20
Copper Creek	Copper Creek	1.9	131.0	2.5	2.4	64.0	50.0	74.0	7.5	1.40
Sowell Ford	Duck	159.4	1025.0	2.1	5.2	198.0	192.0	234.0	1.4	0.27
Lillard Mill	Duck	179.1	916.0	4.1	3.5	232.0	198.0	262.0	1.5	0.28
Halls Mill	Duck	202.2	589.0	4.9	3.1	148.0	72.0	232.0	1.8	0.34
Dement Bridge	Duck	243.1	221.0	1.5	2.6	149.0	122.0	172.0	4.1	0.78
Elk	Elk	91.4	846.0	4.1	4.0	148.0	120.0	148.0	1.9	0.36
Hale Bridge	Nolichucky	27.8	1289.0	4.0	5.3	192.0	164.0	458.0	5.3	1.00
Click Island	N. Fork Holston	6.2	677.0	2.3	2.5	244.0	210.0	268.0	4.5	0.85
Saltville	N. Fork Holston	85.2	221.0	2.1	1.7	88.0	196.0	68.0	10.0	1.90
Estill Fork	Paint Rock	60.0	99.5	3.7	3.0	76.0	54.0	110.0	6.2	1.20
Buchanan Ford	Powell	99.2	540.0	2.4	3.2	143.0	116.0	170.0	2.0	0.38
Fletcher Ford	Powell	117.4	464.0	4.6	4.2	148.0	92.0	194.0	1.9	0.36

*From random sampling of mussels, adjusted to average flow conditions.
†Mean depth from centerline values at 50-foot intervals under average flow conditions.
‡Mean width from 50-foot intervals under average flow conditions.
§Percent X 10 Example: 10 ft/1000 ft = 1 percent = 10 0/00.

The study reaches with relatively high stream gradients (equal to or greater than six feet per mile) are Fort Blackmore (Clinch); Copper Creek, Saltville (N. Fork Holston); and Estill Fork (Paint Rock). Reaches with relatively low gradients are Kyles Ford (Clinch); Sowell Ford, Lillard Mill, and Halls Mill (Duck); Elk; and Buchanan Ford and Fletcher Ford (Powell). These all had gradients less than two feet per mile.

Stage discharge relationships were established for all the reaches based on the field sampling data. The results are shown in Appendix A, Figures A1 through A15.

Hydrologic Data

Long-term average flow provides an easily accessible means of characterizing long-term flow conditions. Low flow data show streams that essentially pool with little or no flow, while flood conditions and floodplain information show areas that may have significantly high velocities. Table 3 provides a summary of long-term flow information for each reach. Table 4 provides a list of the stream gages near each reach which were used in these comparisons.

Several of the study reaches are downstream of control dams that can act to supplement flow during normally dry periods and prevent floods during severe rains. The reaches influenced by dam releases are all the Duck River reaches (downstream of Normandy Dam) and the Elk River reach (downstream of Tims Ford Dam).

The liability to drought may be particularly important to mollusks. Mauch (1963) observed that when the water recedes, mussels retire into substratum, close their shells and wait, making no attempt to follow the water's edge. In this condition they may survive for a few days but not for extended periods (Hynes, 1970).

To characterize low flow conditions, the 7-day duration flow which occurs at a frequency of once in 10 years ($_7Q_{10}$) was determined from past water records at stream gages near each reach. These results are also shown in Table 3. Most of the mussel sampling that was carried out for other program activities was done during the summer of 1980 which

Table 3. Summary of flow information for CMCP study reaches.

CMCP Reach	River	RM	Drainage Area (mi^2)	7Q10* (cfs)	Average Flow (cfs)	20-Year Recurrence Flood (cfs)	Flood† Average	Immediate Floodplain
Topsy Bridge	Buffalo	79.9	342	86	579	43,500	75‡	Narrow
Kyles Ford	Clinch	189.5	1268	110	1806	52,000	29	Wide
Fort Blackmore	Clinch	227.4	897	70	1267	38,000	30	Wide
Copper Creek	Copper Creek	1.9	131	21	174	8,500	50	Wide
Sowell Ford	Duck	159.4	1025	32	1714	41,000	24	Narrow
Lillard Mill	Duck	179.1	916	38	1558	39,000	25	Narrow
Halls Mill	Duck	202.2	589	47	1002	32,000	32	Narrow
Dement Bridge	Duck	243.1	221	36	386	7,500	20	Wide
Elk	Elk	91.4	846	136	1495	4,000	16	Wide
Hale Bridge	Nolichucky	27.8	1289	238	2098	60,000	29	Wide
Click Island	N. Fork Holston	6.2	677	56	921	31,500	34	Wide
Saltville	N. Fork Holston	85.2	221	22	303	14,000	46	Wide
Estill Fork	Paint Rock	60.0	99.5	<1‡	216	16,000	74	Wide
Buchanan Ford	Powell	99.2	540	64	910	31,000	34	Narrow
Fletcher Ford	Powell	117.4	464	49	782	31,000	40	Medium

*10-year recurrence low flow lasting 7 days in duration.
†Ratio of 20-year flood and average flow.
‡Particular problem discussed in text.

Table 4. Stream gages with long-term records near the CMCP reaches.

CMCP Reach	River	State	River Mile	Downstream		Upstream	
				No.*	RM	No.*	RM
Topsy Bridge	Buffalo	TN	79.9	6040	58.7	59†	104.5
Kyles Ford	Clinch	TN	189.5	5280	159.8	5270	211.0
Fort Blackmore	Clinch	VA	227.4	5270	211.0	5240	271.6
Copper Creek	Copper Creek	VA	1.9				
Sowell Ford	Duck	TN	159.4	5995	132.8	5260	12.7
Lillard Mill	Duck	TN	179.1	5995	132.8	5980	216.2
Halls Mill	Duck	TN	202.2	5995	132.8	5980	216.2
Dement Bridge	Duck	TN	243.1	5980	216.2	5980	216.2
Elk	Elk	TN	91.4	5825	89.8	5960	265.4
Hale Bridge	Nolichucky	TN	27.8			4665	45.7
Click Island	N. Fork Holston	VA	6.2			4900	8.8
Saltville	N. Fork Holston	VA	85.2	4880	85.0		
Estill Fork	Paint Rock	AL	60.0	5745	26.6		
Buchanan Ford	Powell	TN	99.2	5320	65.4	5315	143.1
Fletcher Ford	Powell	VA	117.4	5320	65.4	5315	143.1

*No. is USGS number shown in yearly Water Resources Data.
†Number from "Stream Gages in the Tennessee River Basin" (TVA, 1970).

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provided the lowest flow conditions in recent history. The stage readings during these sample periods show that most of the sampling was done close to estimated $_7Q_{10}$ flow.

Based on water elevations at the reach existing under $_7Q_{10}$ flow conditions, reach map topography was used to point out potential dry areas. The significant problem areas include the middle section of Estill Fork (Paint Rock) and the downstream portion at Fletcher Ford (Powell). Estill Fork (Paint Rock) is the most serious, since essentially no flow would exist and remaining water would be in pools.

Streams which are susceptible to floods have less abundant and varied benthic fauna (Hynes, 1970). To determine if an area is particularly subject to problems associated with flooding, 20-year recurrence flood was evaluated. The results are included in Table 3. The floods were all more than one order of magnitude higher than average flows. Reaches with the highest increase over the average flow were compared using the floodplain in the immediate area to determine the potential for severe washout conditions. The only reach with this potential problem is Topsy Bridge (Buffalo) which had the largest percent increase of all the reaches and is located in a very narrow area.

Flow duration curves were also developed for each of the reaches. These curves are based on long-term data from nearby stream gages, adjusted by a drainage area ratio. The specific curves are shown in Appendix B, Figures B1 through B15. Summaries of these data appear in Table 5, which shows the 20, 50, and 80 percent exceedance values.

The shape of the duration curve provides a picture of the nature of the streamflow. A steep curve at high flows indicates a river has flash floods while a steep curve at low flows suggests a river is subject to very low flows. A flat curve is found in a river with few floods (Wisler and Brater, 1959). The river sites which show particularly steep flow duration curve slopes are Sowell Ford and Lillard Mill (Duck), Estill Fork (Paint Rock), and Topsy Bridge (Buffalo). The flow duration curve at Topsy Bridge (Buffalo) is steep only in the upper flows and flattens out at low flows. Copper Creek and Hale Bridge (Nolichucky) have the least slope in the main portion of the curve showing less

Table 5. Summary of flow duration curves for CMCP study reaches.

CMCP Reach	River	Drainage Area (mi^2)	Daily Average Flow Equal to or Less (Percent of Time) 20 (cfs)	20 (cfs/mi^2)	50 (cfs)	50 (cfs/mi^2)	80 (cfs)	80 (cfs/mi^2)
Topsy Bridge	Buffalo	342	200	0.585	350	1.023	800	2.339
Kyles Ford	Clinch	1268	325	0.256	900	0.710	2500	1.972
Fort Blackmore	Clinch	897	200	0.223	650	0.725	1800	2.007
Copper Creek	Copper Creek	131	40	0.305	90	0.687	350	2.672
Sowell Ford	Duck	1025	150	0.146	550	0.537	2500	2.439
Lillard Mill	Duck	916	130	0.142	500	0.546	1900	2.074
Halls Mill	Duck	589	150	0.255	350	0.594	1400	2.377
Dement Bridge	Duck	221	80	0.362	180	0.814	525	2.376
Elk	Elk	846	280	0.331	710	0.839	2100	2.482
Hale Bridge	Nolichucky	1289	900	0.698	1400	1.086	2750	2.133
Click Island	N. Fork Holston	677	160	0.236	425	0.628	1200	1.773
Saltville	N. Fork Holston	221	55	0.249	150	0.679	400	1.810
Estill Fork	Paint Rock	99.5	10.8	0.109	57.1	0.574	265	2.663
Buchanan Ford	Powell	540	220	0.370	575	1.065	1500	2.778
Fletcher Ford	Powell	464	110	0.237	350	0.754	1110	2.392

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tendency for flash floods. Eight of the reaches show surprisingly similar slopes over the entire range of flows. These include Kyles Ford and Fort Blackmore (Clinch); Halls Mill (Duck); Elk; Click Island and Saltville (North Fork Holston); and Buchanan and Fletcher Ford (Powell). The flow duration curve for Dement Bridge (Duck) was similar to the previous eight but flattened out sooner at low flow conditions. The Topsy Bridge (Buffalo) reach shows up again as having the potential for flooding problems.

The high potential flooding conditions at Topsy Bridge can be explained by the upstream tributary pattern and surrounding geology. The high flood/average flow is most likely due to the dendritic pattern of tributary streams which accumulate water quicker than the study reaches on the more linear Duck River and other eastern area rivers. Most of the western area reaches showed steeper duration curves, conceivably due to soil conditions in the region. The near-surface geology in middle Tennessee consists of limestone with a thick overlying layer of clay. Surface runoff is, therefore, higher than in areas that can absorb more water into the soil.

Velocity measurements were taken over a range of flow conditions at three cross sections in each study reach. Since river discharges vary considerably, velocity distributions are also quite variable. General patterns related to topography are, however, identifiable. Normally currents vary according to channel depth in both lateral and vertical directions. The highest velocity in any straight symmetric channel is usually at the surface in mid-channel. Low flows generate low velocities especially in shallow areas near the banks. Each of the reaches showed this general pattern with specific deviations due to river curves, islands, shallow areas, etc.

As a means of comparing reaches, the average velocity at the three measured cross sections determined at average flow conditions is listed in Table 6. These average velocities correlate well with the general size (drainage area) of each study reach. Specific geographical remarks about each study reach are also included in Table 6 regarding effects on the velocity distributions.

Table 6. Velocity distributions at the CMCP reaches.

CMCP Reach	River	Average* Velocity (ft/sec)	Remarks
Topsy Bridge	Buffalo	2.3	deep right bank, rock
Kyles Ford	Clinch	3.0	normal velocity distribution
Fort Blackmore	Clinch	3.5	normal velocity distribution, left bank deeper
Copper Creek	Copper Creek	2.2	straight channel
Sowell Ford	Duck	4.7	shallow left bank
Lillard Mill	Duck	3.0	braided channel
Halls Mill	Duck	3.7	braided channel, peninsula
Dement Bridge	Duck	2.3	straight channel, bridge piers & island
Elk	Elk	3.4	straight channel
Hale Bridge	Nolichucky	4.6	pool and riffle
Click Island	N. Fork Holston	2.6	shoals just downstream of island
Saltville	N. Fork Holston	2.3	edges deeper
Estill Fork	Paint Rock	2.4	gravel island dominates flow
Buchanan Ford	Powell	3.3	straight, left bank deeper
Fletcher Ford	Powell	2.6	pool and riffle

*Average measured velocity in mid-channel during average flow conditions.

Streambed Composition Data

The composition of the streambed or substrate is an important part of the habitat for aquatic flora and fauna. Benthic aquatic plants are most likely found in areas where roots can develop. Rocky streambeds provide shelter and breeding grounds for fish. Hynes (1970) considered the composition of the substrate to be one of the major factors in the occurrence of benthic organisms. Other researchers have pointed out the strong relationship of substrate with regard to the distribution of mollusks (Harman, 1972) and particularly mussels (Coker, et al., 1921; and Sickel, 1980). Common findings support the variety of substrate requirements of adult mussels depending on species. Isley (1910) pointed out that juvenile mussels may require clean rocky shoals for early development. Coker, et al. (1921), also mentioned that the very young mussels are more sensitive than adults, requiring "delicately balanced conditions" for survival.

The results of the random substrate sampling are presented in Tables 7 and 8. Also provided are percentages of samples found in the various particle size categories on the surface and at a 3-inch depth.

Two study reaches had one predominant substrate type at the surface; Dement Bridge (Duck), 89 percent gravel and Saltville (North Fork Holston), 70 percent rock. Seven of the reaches had quite variable surface substrates with no more than about 50 percent in a single category. Several other sites bordered on having variable substrates with significant percentages in both small (silt/clay or sand) and large (gravel, cobble, or rock) size categories.

Most of the substrate sampled at the 3-inch depth fell into one or two size categories. The most common subsurface materials were sand, gravel, and rock. More sites showed predominantly single substrate types at the 3-inch depth than at the surface. Fort Blackmore (Clinch) and Buchanan Ford (Powell) had mostly gravel (63 percent and 76 percent, respectively) while Copper Creek and Dement Bridge (Duck) had mostly sand (85 percent and 76 percent, respectively). Few sites showed the variability of material found in the surface sampling.

Since flow characteristics are influenced by the streambed topography, the substrates normally correlate with general topographic

Table 7. Summary of surface substrate sampling results at the CMCP study reaches.

CMCP Reach	River	Percentage of Samples in Given Particle Site Category					Remarks
		Silt/Clay	Sand	Gravel	Cobble	Rock	
Topsy Bridge	Buffalo	28	24	14	32	1	variable, no rock
Kyles Ford	Clinch	5	19	22	34	21	variable, little silt/clay
Fort Blackmore	Clinch	5	2	2	64	27	cobble and rock
Copper Creek	Copper Creek	4	3	44	38	11	gravel and cobble
Sowell Ford	Duck	18	3	42	12	23	variable, little sand
Lillard Mill	Duck	30	10	30	19	11	variable
Halls Mill	Duck	30	6	19	15	30	variable, little sand
Dement Bridge	Duck	1	3	89	7	0	gravel
Elk	Elk	13	8	49	31	0	gravel and cobble
Hale Bridge	Nolichucky	28	1	12	56	4	silt/clay and cobble
Click Island	N. Fork Holston	26	29	7	23	15	variable, little gravel
Saltville	N. Fork Holston	0	4	14	11	70	rock
Estill Fork	Paint Rock	17	52	10	17	5	mostly sand
Buchanan Ford	Powell	7	28	6	56	3	sand and cobble
Fletcher Ford	Powell	23	19	4	51	3	variable, little gravel or rock

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Table 8. Summary of subsurface substrate (3-inch depth) sampling results at the CMCP study reaches.

CMCP Reach	River	Percentage of Samples in Given Particle Site Category					Remarks
		Silt/Clay	Sand	Gravel	Cobble	Rock	
Topsy Bridge	Buffalo	7	13	42	28	10	variable
Kyles Ford	Clinch	2	30	28	3	36	rock, gravel and sand
Fort Blackmore	Clinch	5	8	63	14	11	mostly gravel
Copper Creek	Copper Creek	10	85	3	0	3	mostly sand
Sowell Ford	Duck	7	15	24	1	52	rock, gravel and sand
Lillard Mill	Duck	12	30	35	0	24	variable, no cobble
Halls Mill	Duck	12	8	21	5	54	rock and gravel
Dement Bridge	Duck	5	76	17	1	0	mostly sand
Elk	Elk	12	51	33	4	0	sand and gravel
Hale Bridge	Nolichucky	11	13	19	21	37	variable, more rock
Click Island	N. Fork Holston	6	25	28	23	17	variable, low silt/clay
Saltville	N. Fork Holston	20	22	47	3	6	gravel,sand, and silt/clay
Estill Fork	Paint Rock	9	42	47	3	0	gravel and sand
Buchanan Ford	Powell	3	1	76	19	3	gravel
Fletcher Ford	Powell	11	24	55	7	4	gravel and sand

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features. River reaches with steep slopes and associated high velocities have surface substrates that are relatively free of fine material. The size of substrate particles normally decreases from rock and cobble at midchannel to silt/clay material near the banks. Decreasing depth and associated lower currents account for this trend. Shallow depths with normally low velocities produce areas where the fine materials are deposited and not washed away. Very deep areas sheltered from high currents also have deposits of fine material.

Subsurface substrates did not show the strong correlation with topography and velocities seen at the surface. Sand, gravel, and rock were fairly evenly scattered in distribution.

Suspended Sediment Data

Suspended sediment can influence aquatic habitats through effects on light penetration (turbidity) and potential sediment deposition during low flow conditions. Field measurements of suspended sediment concentrations were taken at each of the study reaches under a variety of flow conditions. The resulting data were used to evaluate lateral suspended sediment distributions, to estimate concentrations under average flow conditions, and to estimate average annual sediment loadings.

Several watersheds in the Tennessee Valley were studied extensively for suspended sediment loads during 1935-37 and 1963-65 (TVA, undated). Table 9 shows the resulting average annual loadings for the rivers studied in the CMCP. The Nolichucky River had the highest loadings (study reach ended at Nolichucky Dam). Duck and Elk Rivers were in a middle range while the lowest loadings were found in the Clinch and North Fork Holston study watersheds.

CMCP study reach surveys used integrated depth sampling at five points across each cross section. Lateral differences in the measured suspended sediment concentration occur due to variations in stream depth. The deeper areas have higher velocities with more capacity to hold the suspended material. There are no significant site-to-site differences in lateral distributions that warrant specific comparisons.

Table 9. Summary of suspended sediment load studies in Tennessee River Valley (TVA, undated).

Rivers	Drainage Area (mi^2)	Average Annual Load ($tons/mi^2$) 1935-37	1963-65
Clinch River at Speers Ferry, VA	1126	336	242
Duck River at Hurricane Mills, TN	2557	796	411
Elk River near Prospect, TN	1784	1097	380
Nolichucky River at Embreeville, TN	805	981	708
North Fork Holston River near Gate City, VA	672	304	210

The results of the suspended sediment sampling are detailed in the sediment-discharge graphs shown in Appendix C, Figures C1 through C15. Summary numbers, suspended sediment at average flow conditions, and estimated average annual loadings are shown in Table 10. The average flow calculations probably are more reliable than the sediment load values because most of the field measurements were taken near average flow conditions. Field measurements at very high flows, necessary to do accurate annual sediment load calculations, could not be obtained at all of the study reaches. Suspended sediment values at average conditions can be used to make a comparison based on the same flow conditions while the annual sediment loads are normalized based on drainage area considerations.

The calculated annual average sediment loads for the study reaches were compared to other studies involving watershed size (drainage area) and sediment yield. Glymph (1951) studied 51 watersheds in 20 states and produced enveloping curves of sediment yields in tons per square mile versus drainage area in square miles. Three CMCP study reaches fall below the envelope: Dement Bridge (Duck), Saltville (N. Fork Holston), and Estill Fork (Paint Rock). Topsy Bridge (Buffalo) and Lillard Mill (Duck) were both near the lower enveloping curve. These five study reaches fall into a class expected to have lower sedimentation effects for their drainage areas. All the other study reaches fall within the enveloping curves found by Glymph.

Fleming (1969) produced a single line representing average annual sediment load trends based on 250 watersheds on four continents. Five CMCP study reaches fall above this line: Elk River; Fletcher Ford and Buchanan Ford (Powell); Halls Mill (Duck); and Kyles Ford (Clinch) appear to have sediment yields larger than Fleming's graph of drainage area values would predict. The five remaining study reaches are all near the average trend line shown by Fleming and have sediment yields that can be considered typical for their drainage areas.

The calculated values for suspended sediment concentrations at average flow were used to associate the study reaches at comparable flow conditions. Topsy Bridge (Buffalo); Copper Creek; Dement Bridge (Duck);

Table 10. Summary of suspended sediment evaluations at the CMCP study reaches.

CMCP Reach	River	Drainage Area (mi^2)	Average Flow* (cfs)	Suspended Sediment Concentration at Average Flow (ppm)	Average Annual Suspended Sediment Load (tons/mi^2)
Topsy Bridge	Buffalo	342	579	12	114
Kyles Ford	Clinch	1268	1806	33	588
Fort Blackmore	Clinch	897	1267	67	219
Copper Creek	Copper Creek	131	174	15	245
Sowell Ford	Duck	1025	1714	27	170
Lillard Mill	Duck	916	1558	21	87
Halls Mill	Duck	589	1002	25	586
Dement Bridge	Duck	221	386	15	39
Elk	Elk	846	1495	42	1413
Hale Bridge	Nolichucky	1289	2098	131	269
Click Island	N. Fork Holston	677	921	34	206
Saltville	N. Fork Holston	221	303	20	53
Estill Fork	Paint Rock	99.5	216	8	31
Buchanan Ford	Powell	540	910	61	622
Fletcher Ford	Powell	464	782	55	691

*Average flow based on drainage area conversion of the average discharge for the nearest gage reported in U.S. Geological Survey Water Data Reports.

and Estill Fork (Paint Rock) all had concentrations less than or equal to 15 ppm (mg/L). The highest value was found at Hale Bridge (Nolichucky) at 131 ppm. Other reaches with averages higher than 50 ppm included Fort Blackmore (Clinch), Buchanan Ford (Powell), and Fletcher Ford (Powell). The remaining seven reaches all had average flow concentrations in the range of 15 to 50 ppm.

The study reaches most likely to exhibit sedimentation effects include both of the Powell River reaches (Fletcher Ford and Buchanan Ford), Elk River, both of the Clinch River reaches (Kyles Ford and Fort Blackmore), Hale Bridge on the Nolichucky River, and Halls Mill on the Duck River. Relatively few data points from the Elk River reach produced a high average annual suspended sediment load value as well as a relatively high sediment concentration at average flow. Large sedimentation effects in the Clinch and Powell Rivers may be attributable to the extensive surface coal mining activities in the watersheds. The Nolichucky River watershed has a significant number of surface mica and feldspar mines. Agricultural sources and poor land use may be the most significant causes of suspended sediment at the Duck and Elk River sites.

Study reaches with little sedimentation include Estill Fork (Paint Rock), Dement Bridge and Lillard Mill (Duck), Saltville (North Fork Holston), and Topsy Bridge (Buffalo). The low suspended sediment values at the Dement Bridge (Duck) site may be related to the effects of Normandy Dam, not far upstream. The Lillard Mill Dam also may affect the low suspended sediment measurements taken at this study reach.

Summary Data

Table 11 provides a comprehensive summary of the most significant data used to characterize each study reach.

The drainage area for each reach is listed to provide a means of comparison by general size. Flow conditions generally follow comparisons made for drainage area.

River gradient was chosen as a summary parameter since it is often used in characterizing fish habitat. In general, there is an inverse relationship between relative size and gradient. The larger sites have low gradients while the smaller sites have high gradients.

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Table 11. Summary information for CMCP physical characterization.

CMCP Reach	River	Drainage Area (mi^2)	Stream Gradient (Slope) (ft/mi)	Average Velocity* (ft/sec)	Surface Substrate†	Subsurface Substrate†	Suspended Sediment‡ (ppm)	Special Remarks
Topsy Bridge	Buffalo	342	3.4	2.3	V	V	12	flooding
Kyles Ford	Clinch	1268	2.0	3.0	V	SGR	33	
Fort Blackmore	Clinch	897	6.4	3.5	CR	G	67	
Copper Creek	Copper Creek	131	7.5	2.2	GC	S	15	small
Sowell Ford	Duck	1025	1.4	4.7	V	SGR	27	
Lillard Mill	Duck	916	1.5	3.0	V	V	21	braided
Halls Mill	Duck	589	1.8	3.7	V	GR	25	braided
Dement Bridge	Duck	221	4.1	2.3	G	S	15	controlled flow
Elk	Elk	846	1.9	3.4	GC	SG	42	controlled flow
Hale Bridge	Nolichucky	1289	5.3	4.6	FC	V	131	high suspended sediment
Click Island	N. Fork Holston	677	4.5	2.6	V	V	34	pool and riffle
Saltville	N. Fork Holston	221	10.0	2.3	R	FSG	20	small
Estill Fork	Paint Rock	99.5	6.2	2.4	S	SG	8	low flow
Buchanan Ford	Powell	540	2.0	3.3	SC	G	61	high suspended sediment
Fletcher Ford	Powell	464	1.9	2.6	V	SG	55	high suspended sediment

*Average measured velocity in mid-channel during average flow conditions.
†V = variable, F = silt/clay, S = sand, G = gravel, C = cobble, R = rock
‡Suspended sediment concentration at average flow.

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The average velocity determined for average flow conditions should provide some indication of representative velocities. The sites with high measured average velocities are Fort Blackmore (Clinch), Sowell Ford (Duck), and Hale Bridge (Nolichucky). Sites with low measured velocities are Topsy Bridge (Buffalo); Copper Creek, Dement Bridge (Duck); Click Island and Saltville (N. Fork Holston); Estill Fork (Paint Rock); and Fletcher Ford (Powell). Again the velocities correlated well with drainage areas.

The substrates can be compared by the variable nature of the sizes found. The relatively large sites generally have variable substrates while smaller sites show less variability. Normally, higher velocities wash smaller particles to the sides exposing areas of larger materials. The subsurface substrate (at 3-inch depth) showed less variation than the surface, with one or two size categories dominating.

The suspended sediment results point out Hale Bridge (Nolichucky); Buchanan Ford and Fletcher Ford (Powell); Elk River; Kyles Ford and Fort Blackmore (Clinch); and Halls Mill (Duck) with suspended sediment concentrations that are higher than other sites. Sites with relatively low suspended sediment concentrations are Topsy Bridge (Buffalo), Saltville (North Fork Holston), Estill Fork (Paint Rock), and Dement and Lillard Mill (Duck). The remaining sites can be classified as having moderate potential impact from suspended sediment. This includes the Sowell (Duck), Copper Creek and Click Island on the N. Fork Holston River.

Special remarks about each reach are also provided based on input from all the evaluations. These identify any specific concern about the reach.

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TASK II - INSTREAM STRUCTURES ANALYSIS

Task II of the CMCP Activity 5 studied the effects of instream structures (mill or low-head dams) on the downstream physical environment. There was hope that the recent interest in low-head dams (potential refurbishment for power generation) would provide applicable literature on downstream environmental effects. However, the main environmental concerns associated with low-head dam development were related to effects on fish passage and changes to the normal storage and release patterns of impoundments. Potential drying of the river bed, under storage conditions, was a major complicating factor (TVA, 1982). Specific concerns due to possible water level fluctuation have been studied by Hildebrand, ed. (1980). The principal identified problems below the low-head dams due to water level changes were (1) streambed and bank erosion and (2) water quality problems related to resuspension and redistribution of eroded materials. Since the dam at Lillard Mill is a run-of-the-river structure not capable of changing release patterns, most of the concerns identified by recent studies were not applicable. Therefore, a specific study of downstream hydraulic effects from run-of-the-river, low-head dams was conducted.

TASK II METHODS

Field reconnaissance of several low-head dam sites consisted of recording the general site features on photographs, preliminary mapping of the areas, and general hydraulic measurements. Aerial photographs of the Lillard Mill area were obtained from TVA's Mapping Services Branch, Division of Natural Resource Operations. Field investigations of the Lillard Mill site included detailed topographic surveys of the river from the dam downstream to the edge of the study reach identified in Task I. Preliminary mapping of substrates and substrate grab samples taken during the Activity 8 mussel sampling were used to characterize the river bottom. Aquatic vegetation maps from Activity 7 were used to determine additional influences on the flow.

The modeling study of the Lillard Mill area used a two-dimensional, staggered-grid, finite-difference mathematical model. The model developed by Tatom and Smith (1981) was adapted for use at this site using bottom topography and variable bottom roughness obtained from the field survey data. Upstream boundary conditions were based on the long-term average flow as reported by the U.S. Geological Survey. The model was verified using field measurements of velocities taken during Task I of Activity 5 and general flow characteristics observable at the site.

TASK II FIELD INVESTIGATIONS

Other Low-Head Dam Sites

Field reconnaissance of several low-head dams was used to obtain a general idea of the effects of these types of structures on downstream environment. Sites were selected from an inventory of small hydro sites, part of TVA's small hydro program feasibility study (TVA, 1982). Dams with hydraulic characteristics similar to those at Lillard Mill were chosen for study (head, dam height, average flow and drainage area). Table 12 provides a summary of the four sites as they compare with Lillard Mill. The following briefly summarizes the variable effects seen at the sites.

The dam at Peery Mill on the Little River extends the width of the river providing flow to the right side of the downstream area. The bulk of the flow downstream of the dam remains in the original channel.

The dam at Pigeon Forge on the West Prong of the Little Pigeon River is not significantly wider than the width of the river at Peery Mill. The river is channelized both upstream and downstream of the dam. There are several rock outcroppings but no specific downstream effects are obvious.

At the Townsend Light Dam site on the Little River the dam width is much greater than the original river. However, a steep downstream gradient causes water to flow in the original channel area.

Table 12. Summary of hydraulic characteristics for field-surveyed dams.

Site Name	River and State	River Mile	Drainage Area (mi^2)	Average Flow (cfs)	Dam Height (ft)	Dam Head (ft)	Approximate Width (ft)
Lillard Mill	Duck, TN	179.2	916	1558	11	11	150
Peery Mill	Little, TN	21.9	189	378	7.6	7.6	220
Pigeon Forge	West Prong Little Pigeon, TN	10.9	74.7	119.6	16	16	60
Townsend Light	Little, TN	33.6	121	242	7.7	10	240
Walker Mill	West Prong Little Pigeon, TN	2.5	148	237	11.5	11.5	120

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The Walker Mill Dam on the West Prong of the Little Pigeon is similar to Peery Mill Dam. The left channel was the original river bed. Flow on the right side of the river passes some islands with heavy vegetation growing into the river. As a result of this most of the downstream flow continues to go into the original channel.

The results of the field surveys show that, depending on dam construction, the major observable effect on the downstream areas is the increase in width of the river occurring under lower flow conditions. The extent of this effect does not normally continue very far downstream because the flow returns to its original channel.

Lillard Mill

According to available history (LaForest and Oliveria, 1979) Lillard Mill was first built in the early 1800s (ca. 1812) with a log dam holding back the Duck River water. The site was named after A. F. Lillard who purchased the mill in 1840. Early use of the mill was primarily for grinding corn for area farmers. From 1849-1870, the water power was also used to turn lathes for making furniture and for carding (disentangling and arranging fibers of cotton, wool, flax, etc., before spinning).

A 1902 flood washed the log dam and mill structure downstream. In 1924-25 the present dam and concrete building were built by Lewisburg Power and Light Company to generate power. The structure/facilities were later acquired by Tennessee Electric Power Company, which sold the property to Mr. R. R. Lunn. After attempts to sell the site to developers failed, Mr. Lunn sold the property to the city of Lewisburg which still uses the mill pond as its sole water supply.

TVA field investigation reports from 1947 and 1954 (Beverage to Goddard, 1947, Manthey to Beverage, 1954) state the powerhouse was abandoned in 1936 or 1937 with all equipment removed at that time. The dam is reported as a concrete gravity-section about 250-300 feet in length. The dam is about 18 feet with a normal operating head (forebay to tailrace) of 11 feet. The dam and brick powerhouse appear in good condition to this date.

Aerial photographs of the Lillard Mill area were available from February 3, 1946, March 31, 1966, and March 6, 1980. The islands located downstream of the dam are easily identified in the 1980 and 1966 photos. Traces of vegetation at the island locations are also apparent in the 1946 photo taken at high flows. It can be deduced from these photos that the islands have been stable physical features at the downstream locations for many years.

Field investigations in 1983 and topographic surveys were used to identify the physical aspects of the area. The dam is approximately 400 feet upstream of the Lillard Mill study reach detailed in Task I. Figure 62 shows a topographic map of the area from the dam to the downstream edge of the Task I study reach. The powerhouse is located on the right side of the river (facing downstream) creating a 125-foot dam crest. The total length of the dam and powerhouse is approximately 200 feet (this is shorter than previous reports). A rock ledge extends up to 90 feet downstream of the dam creating a natural spillway which prevents extensive scour of the immediate downstream region. Several outcroppings of rock jut out on either side of the river, influencing the river flow at station 8+50 to 9+50 on the left bank and at 7+50 on the right bank. Farther down the reach an island appears just to the right of mid-channel starting at station 5+25 and ending at station 4+00. Two islands dominate the downstream portion of the reach starting at station 1+50.

One basic difference in the hydraulic characteristics of the dam at Lillard Mill compared to other dams discussed previously is the constricting effect of the powerhouse on the river. At most of the other dams studied, the width of the river was extended and some downstream areas were wet under lower flow conditions. The areas produced, off the main channel, had significant island and aquatic vegetation. The islands at the Lillard Mill reach are much farther downstream than those at the other sites and do not appear to be caused by the same mechanisms (distribution of flow across the width of the dam).

TASK II LILLARD MILL DAM SENSITIVITY STUDIES

The constricting effect of the powerhouse was studied using a computer model capable of analyzing flow in the river with and without the dam/powerhouse in place. The following sections describe the model used, application of the model to the Lillard Mill Dam reach, and the resulting effects on the downstream substrate.

Computer Model

A two-dimensional, staggered-grid, finite-difference mathematical model was used to study changes in flow that may affect downstream physical habitat at the Lillard Mill site. A description of the formulation of the model appears in the "Users Manual for XY Plume" (Tatom and Smith, 1981). The model is based on depth-averaged, two-dimensional equations governing conservation of mass and the two horizontal components of momentum.

Modifications to the model were introduced in applying the model to very shallow flow conditions. A staggered-grid concept was used to increase the stability of computations, with velocity components in the x and y directions solved at the corner points and water depth solved at the center points. Other refinements include the capability for grid points to go dry and a more detailed representation of the initial flow field.

Application of Model to Lillard Mill Reach

Application of the computer model to Lillard Mill required detailed bottom topography and substrate and aquatic vegetation information. The banks of the river were first "digitized" to translate exact field-measured dimensions to computer-generated coordinates. A grid was established in the reach which captured the details of topography, substrate, and typical flow field. Figure 63 shows the resulting grid used for the simulation runs at Lillard Mill. Points appearing on Figure 63 are "corner points", where the two-dimensional velocity components are solved. The intersection of grid lines represent "center points" where the water surface elevation is solved.

The detailed topographic survey maps were then used to establish the bottom elevation at all "center points." The resulting computer-generated bottom topographic contour lines are shown in Figure 64. Preliminary substrate mapping and the results of substrate grab samples taken during the mussel sampling were used, along with the vegetation maps developed in Activity 7, to characterize variable bottom roughness at each of the center points. Bottom roughness coefficients were obtained from the guideline values found in Chow (1959).

During both model simulations the long-term average flow (from USGS records) was used as the upstream boundary discharge. The long-term average flow (1558 cfs at Lillard Mill) is always higher than the flow which is exceeded 50 percent of the time. The flow duration curves for the site show the long-term average flow is only exceeded 25 percent of the time. Because the hydraulic effects of the dam are more extensive at higher flows, the long-term average provides a reasonable set of conditions for the hydraulic effects study. The initial surface slope was estimated and initial flow through each section was set equal to the long-term average. The downstream boundary was left open to adjust to discharge and elevation changes as necessary. The model simulations were continued until computed flow in the river stabilized.

Conditions with the dam in place were first modeled to verify computational results with field-measured velocities taken during the Task I studies at the Lillard Mill reach. Figure 65 shows a comparison of the modeled results with velocity measurements during similar flow conditions taken at three cross sections. The field measurements did not include velocity vectors in the horizontal plane. However, the magnitudes (measured with Price current meters) were of most concern for potential effects on downstream substrate. The computer-simulated magnitudes compare very well with the measured values. The double hump velocity distributions are well represented in the model results. The model also compares well with observable flow characteristics in the downstream region. A small circulating eddy zone, identified at the site by a continuing presence of foam, is apparent just downstream of a sand bar on the left side of the river. This appears in the model simulation

at horizontal grid lines J = 8 and 9 on the left side of the river. Some recirculation is also apparent near horizontal grid lines J = 4 and 5 near the right side of the river. This feature was again observed in the field by the presence of a foam pocket. There are also identifiable turbulent zones with "white water" in the mid-channel region just downstream of the dam. The location of the edges of these zones agrees well with transition from high to low velocity vectors seen in the model simulations.

In the second model simulation, the upstream topography was changed by taking out the powerhouse and evenly distributing flow over the cross section at a uniform depth equal to the present depths on the left side of the river. The average flow was again used as the upstream discharge. The resulting velocity vectors are shown in Figure 66. Higher velocities are evident on the right side of the river in the lower half of the reach studied. Because the vector representations are hard to compare, both point comparisons and half-width averages are graphed. The magnitude of the velocity for each corner point along the lateral I = 3, 6 & 9 grid lines (see Figure 63) are shown in Figure 67. The velocities in the reach become nearly equal at the longitudinal J = 17 location, about 530 feet downstream of the dam. A comparison of velocities averaged over the right and left sides of the river is shown in Figure 68. This shows that the average velocities start to compare closely starting at J = 10, about 280 feet downstream of the dam.

Generally, the powerhouse at the dam constricts flow in the river causing higher velocities on the left side of the river. At higher flows the effect on velocities probably reaches farther downstream. The higher velocities keep the left side of the river clear of sediment buildup. The substrate studies also support this conclusion because silted areas (with the dam in place) occur mainly on the right side of the river.

Effects of Dam on Downstream Substrate

Potential downstream hydraulic effects resulting from the dam include bed scouring below the spillway, channel degradation due to

changed sediment load, and flow constriction due to the powerhouse. The flow constriction was considered to be the major potential factor influencing conditions where most of the mussels were found.

Flow in hydraulic jumps (low spillways or weirs) differs from flow in channels in the nature of the vertical velocity distribution. After the jumps, velocities are higher close to the bed, whereas in normal channels maximum velocities occur close to the surface. The main dam design factor is to prevent the problems associated with the sudden ending of a rigid concrete floor followed by an erodable bed (Ahmad, 1953). The area downstream of the spillway at Lillard Mill contains a rock ledge which extends approximately 100 feet downstream. An eroded area just downstream of this ledge does not appear to be significant from the topographic surveys of the site. The fall from the ledge is about one foot. The location of the mussels does not appear to be influenced by the vertical distribution changes since the majority of the mussels are approximately 700 feet downstream of the spillway. Velocity measurements in the Task I study reach were also examined to determine any irregularities in the vertical velocity distribution under both low and high flow conditions. Figures 69 through 71 present three-dimensional representations of the velocities at station 3+00 under three different flows. The figures show higher velocities near the surface which would be typical under normal river conditions. Therefore, the effect of the dam on the downstream vertical velocity profile does not appear to be significant in the area where most of the mussels are found.

If there is substantial removal of sediment load from the outfall of the mill pond and there is sufficient tractive force to initiate movement of materials, downstream channel degradation can take place. The rate of degradation below reservoirs depends on the type of material in the channel and the hydraulic characteristics of the outflow. Clear water discharges can pick up allowable sediment loads by eroding the channel until an equilibrium grade is established. If materials in channel beds are more resistant to erosion than those in the channel banks, bank erosion can take place (Gottschalk, 1968).

Changes in erosion and sedimentation downstream of a dam are mainly attributable to (1) discharge of water from the dam with greatly reduced sediment load and (2) altered periodicity and amplitude of water levels and velocities in the downstream area. Streambeds and banks tend to evolve to a stable condition in response to the range of hydraulic forces that are applied (Taylor, 1978).

The suspended sediment sampling at Lillard Mill detailed in Task I showed lower measurements than all of the other Duck River sites except for Dement Bridge (just downstream of Normandy Dam). The dam may cause some trapping of the suspended material but there did not appear to be significant buildup of sediment upstream of the dam. Measured suspended sediment concentrations were also substantial, meaning the discharge is not very "clear." The dam also does not change the discharge patterns of the river because it is a run-of-the-river dam. Considering the length of time a dam has been at this location, continuing channel degradation effects do not appear to be significant.

The major remaining potential hydraulic effect downstream of the dam is the constriction of flow caused by the powerhouse. The model simulation points out that in the region where most of the mussels were found there does not appear to be a significant change in the distribution of velocities over the width of the river. Most of the mussels were found in the mid-channel area where flows were nearly the same between the simulations. Upstream, closer to the dam, there are higher flows on the left side of the river. The results of the substrate mapping and substrate grab samples confirm that high velocities on the left side of the river lead to cleaner beds. The bulk of the channel areas with deposited material appear on the right side of the river. The mid-channel location of most of the mussels indicates that low flows may be a more important factor in potential hydraulic effects on mussel habitat.

TASK II CONCLUSIONS

The large population of endangered mussels downstream of the Lillard Mill Dam provided the impetus for studying the effects of

instream structures on downstream physical environments. Field reconnaissance of several mill dams with similar hydraulics to the Lillard Mill Dam showed varying downstream conditions. Most of the dams extended the downstream width of the river for a short distance, after which the flow returned to the original river channel.

A detailed study of the Lillard Mill Dam found that the dam and downstream braided complex of islands are stable physical structures in this reach of the river dating back to the 1940s. One basic difference between the Lillard Mill Dam and the other dams studied is the constricting effect of the powerhouse on the river. A two-dimensional computer model was used to identify any lateral changes in flow due to the constriction of the powerhouse. The model was calibrated and run with and without the presence of the dam and powerhouse. Using long-term average flows, this comparison showed the presence of the powerhouse on the dam caused channelization toward the left bank immediately below the dam, but the river gradually returned to its natural channel before reaching the mussel bed.

The downstream substrate, where most of the mussels are found, does not appear to be influenced by any change in the vertical distribution of velocities or channel degradation effects caused by the Lillard Mill Dam. The modeling results showed that a river constriction could be used to keep a particular side of the river clean of sediment. However, the mid-channel velocities in most rivers provide this same cleansing effect. The constriction also does not appear to influence the location of the mussels downstream of the Lillard Mill Dam. The mid-channel location of most of the mussels indicates that low flows, rather than changes in velocities, may exert more potential hydraulic effect on mussel habitat.

The instream structures study did not identify any hydraulic effects on downstream river conditions which would be enhanced by construction of a low-head dam for the purpose of habitat improvement. Other possible effects of the dam, such as sediment trapping, fish migration obstruction, plankton density alterations, etc., were not evaluated under this task. Analyses conducted as a part of other

activities in the CMCP (see the Acitivity 9 report) suggest that suspended sediment and various biological factors are not adequately correlated with mussel presence.

TASK II REFERENCES

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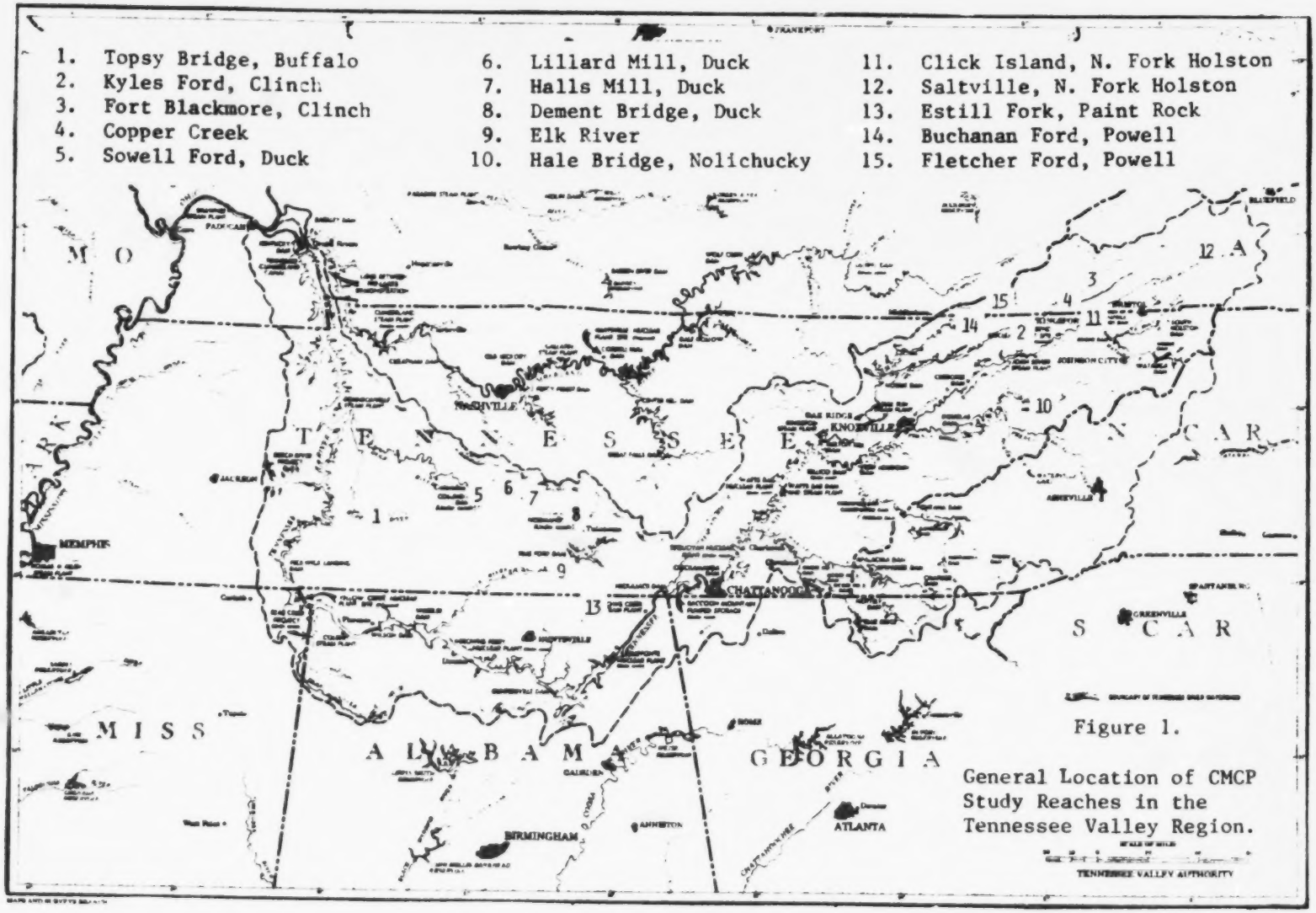

Figure 1.

General Location of CMCP Study Reaches in the Tennessee Valley Region.

55

Figure 2. Topography at Topsy Bridge, Buffalo River, RM 79.9 (from Quadrangle Map 42NW, Topsy, Tennessee).

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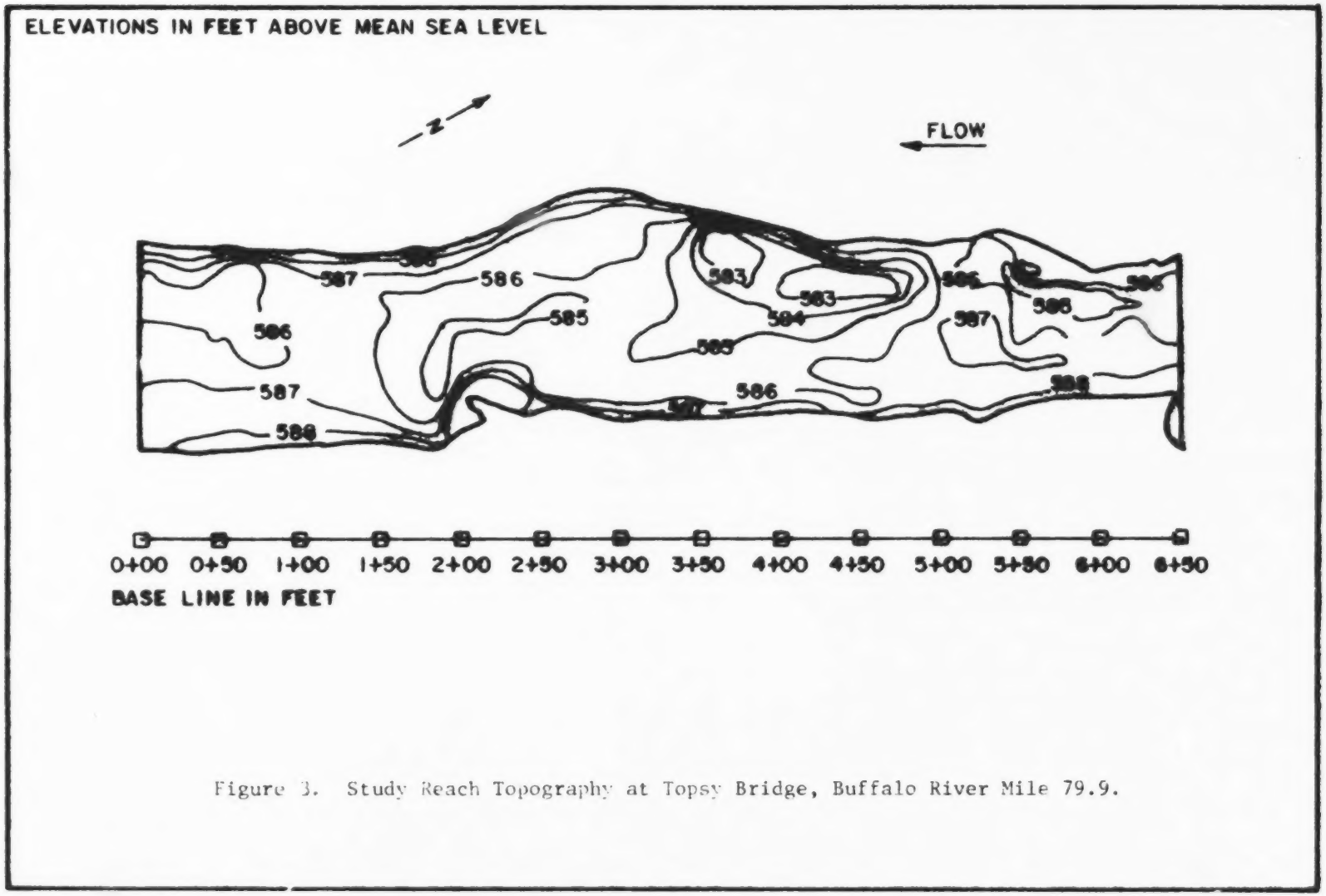

Figure 3. Study Reach Topography at Topsy Bridge, Buffalo River Mile 79.9.

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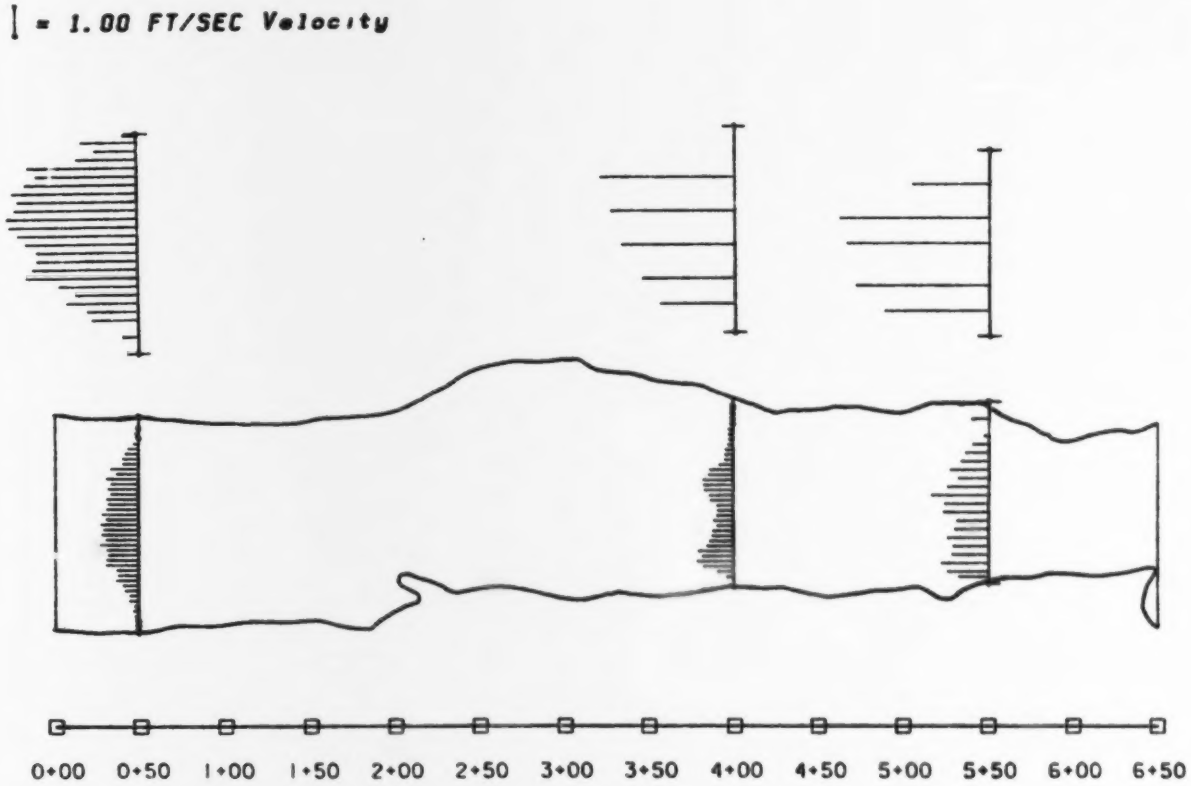

Figure 4. Low and High Measured Velocity Distributions at Topsy Bridge, Buffalo River Mile 79.9.

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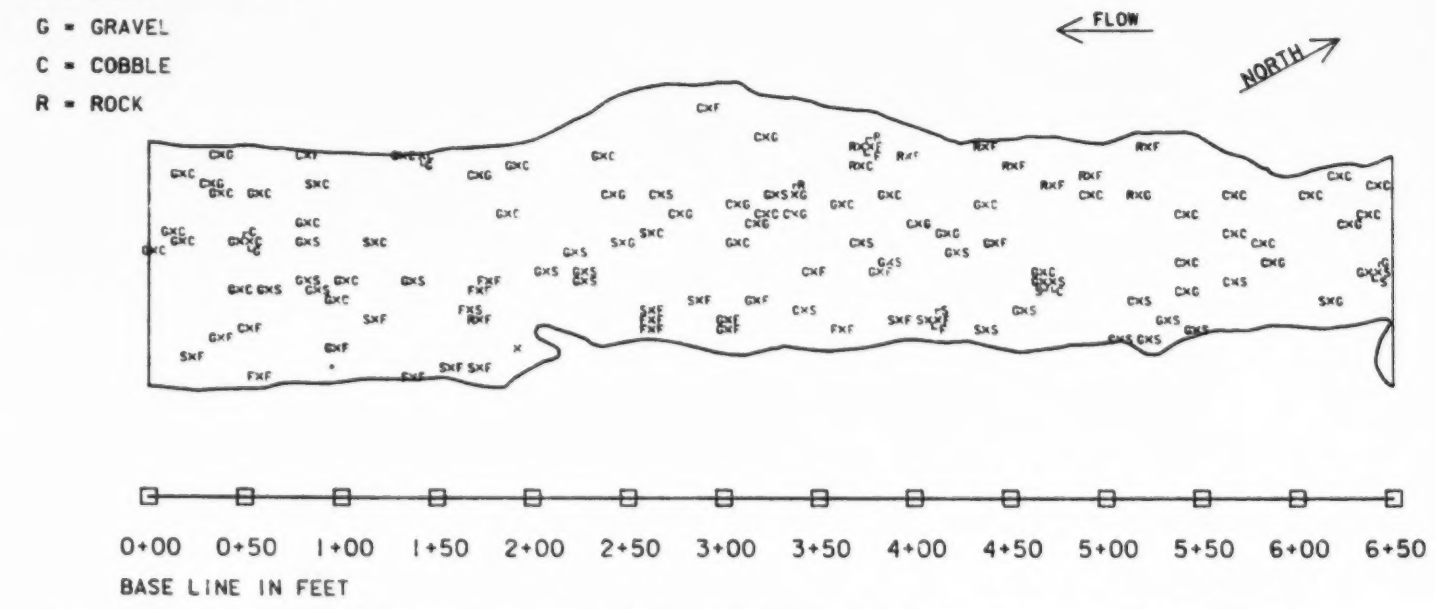

Figure 5. Surface and Subsurface (3-inch Depth) Substrate Composition at Topsy Bridge, Buffalo River Mile 79.9.

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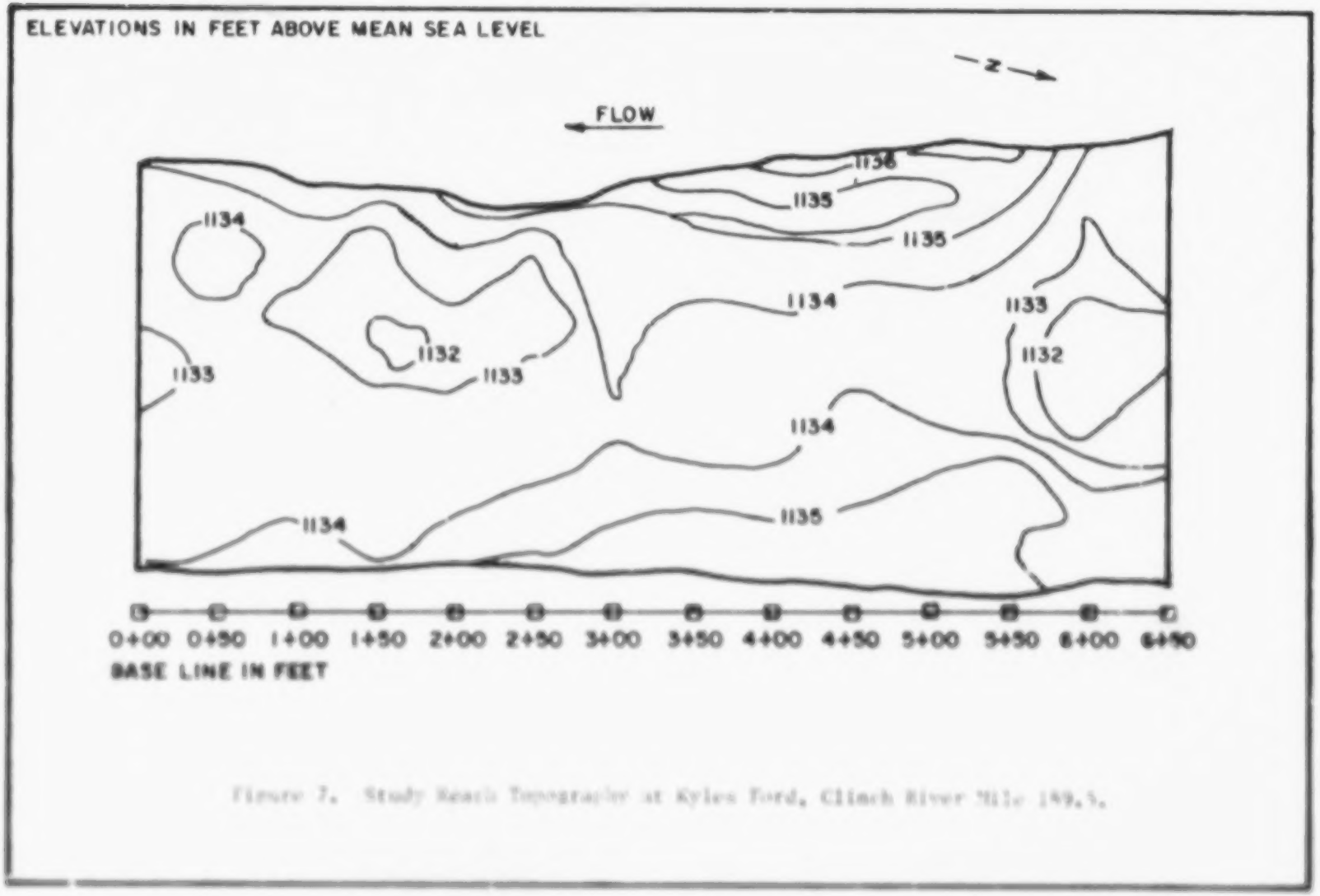

Figure 7. Study Reach Topography at Kyles Ford, Clinch River Mile 149.5.

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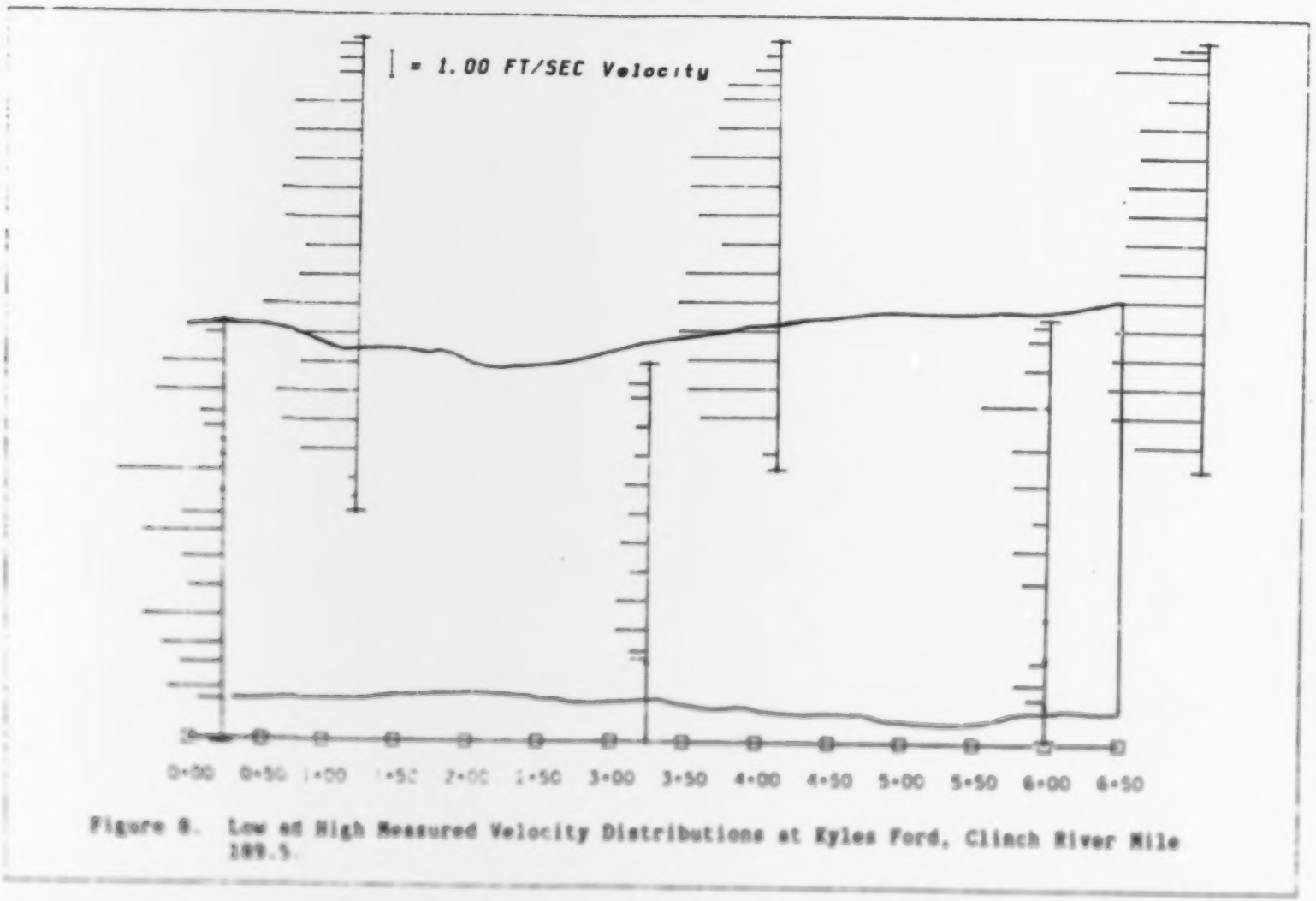

Figure 8. Low ad High Measured Velocity Distributions at Kyles Ford, Clinch River Mile 189.5.

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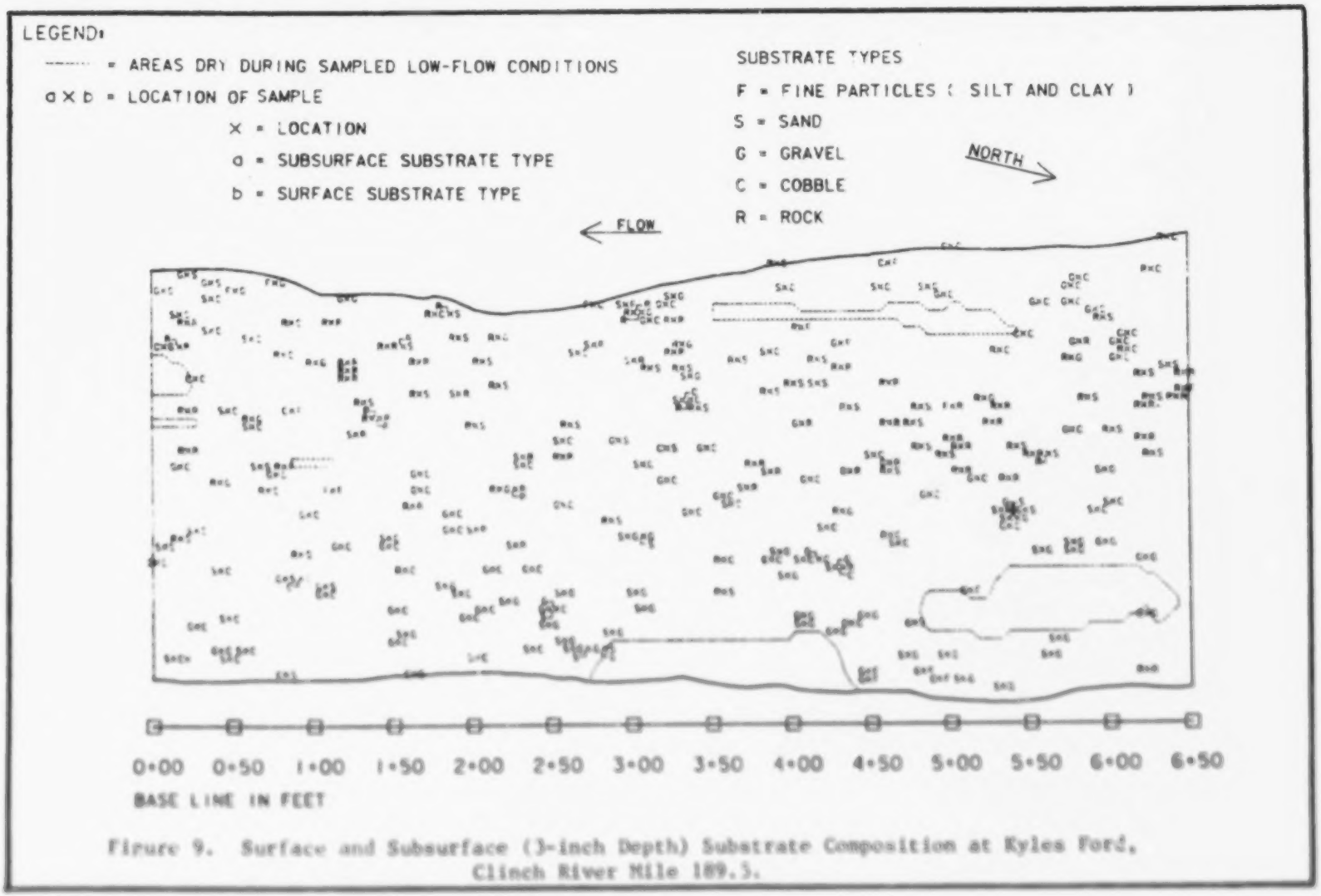
LEGEND:
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a X b = LOCATION OF SAMPLE
X = LOCATION
a = SUBSURFACE SUBSTRATE TYPE
b = SURFACE SUBSTRATE TYPE
SUBSTRATE TYPES
F = FINE PARTICLES (SILT AND CLAY)
S = SAND
G = GRAVEL
C = COBBLE
R = ROCK
NORTH
FLOW
0+00 0+50 1+00 1+50 2+00 2+50 3+00 3+50 4+00 4+50 5+00 5+50 6+00 6+50
BASE LINE IN FEET

Fiure 9. Surface and Subsurface (3-inch Depth) Substrate Composition at Kyles Ford, Clinch River Mile 189.3.

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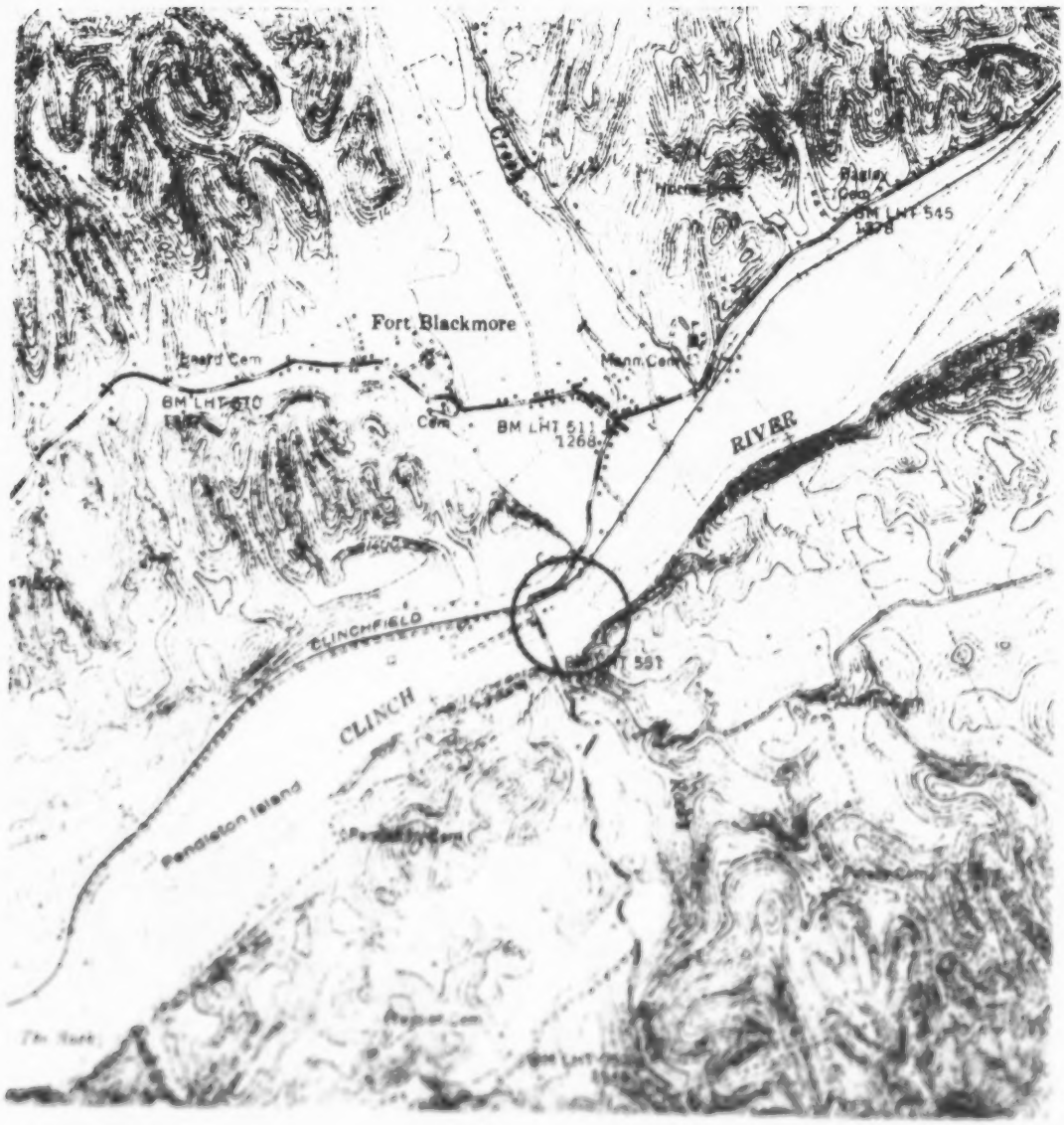

Figure 10. Topography at Fort Blackmore, Clinch River, RM 227.4 (From Quadrangle Map 1678E, Fort Blackmore, Virginia).

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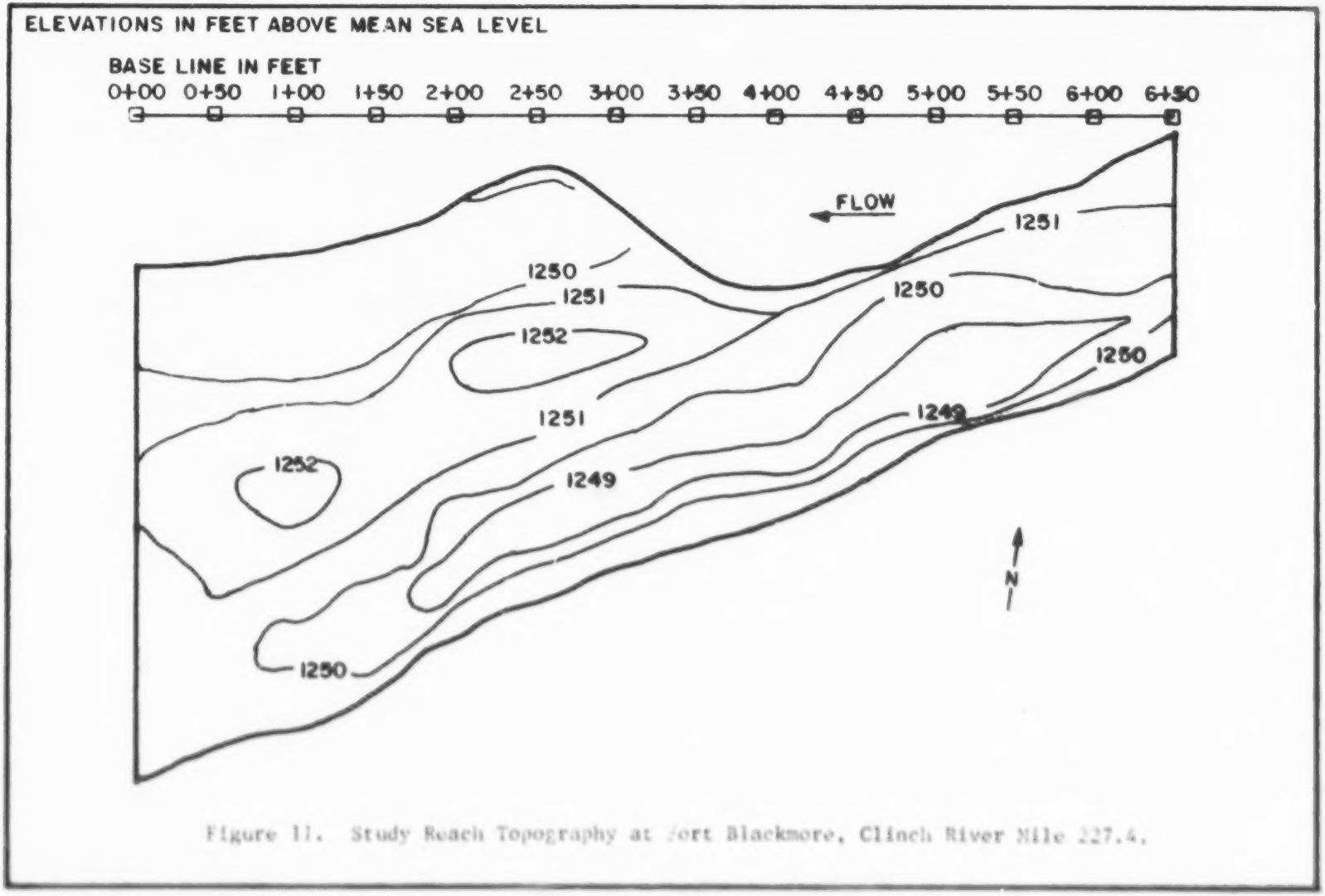

Figure 11. Study Reach Topography at Fort Blackmore, Clinch River Mile 227.4.

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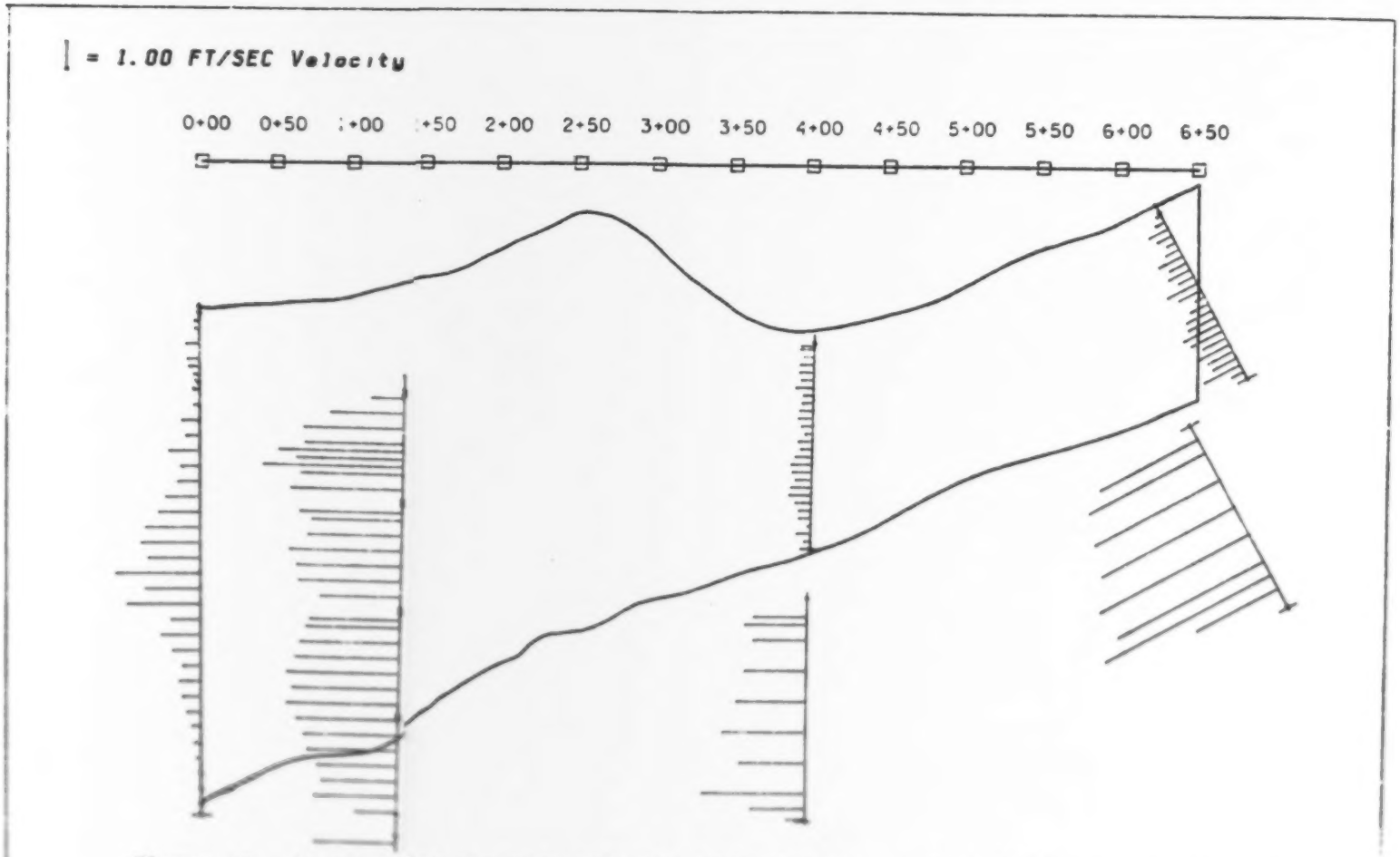

Figure 12. Low and High Measured Velocity Distributions at Fort Blackmore, Clinch River Mile 227.4.

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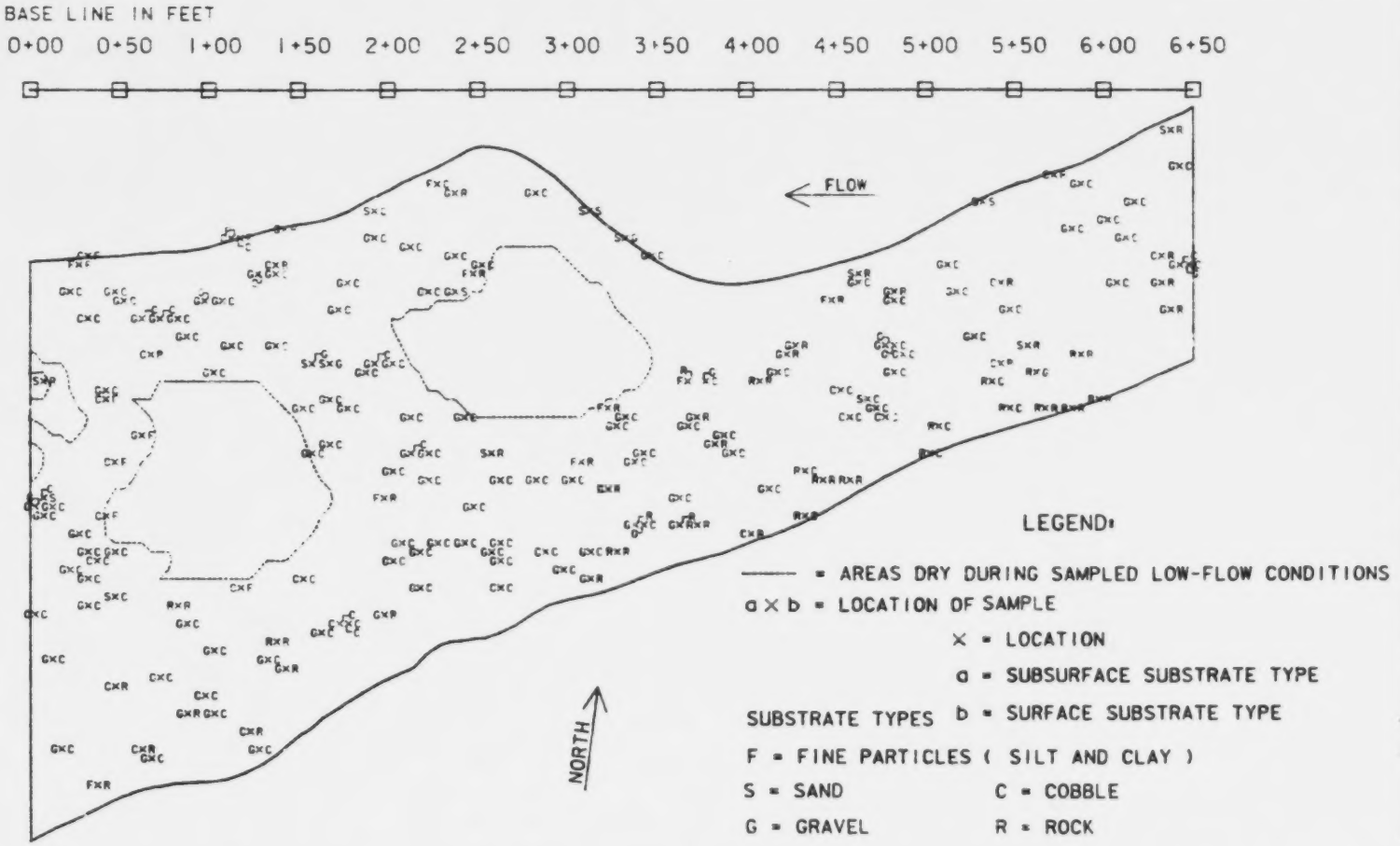

Figure 13. Surface and Subsurface (3-inch Depth) Substrate Composition at Fort Blackmore, Clinch River Mile 227.4.

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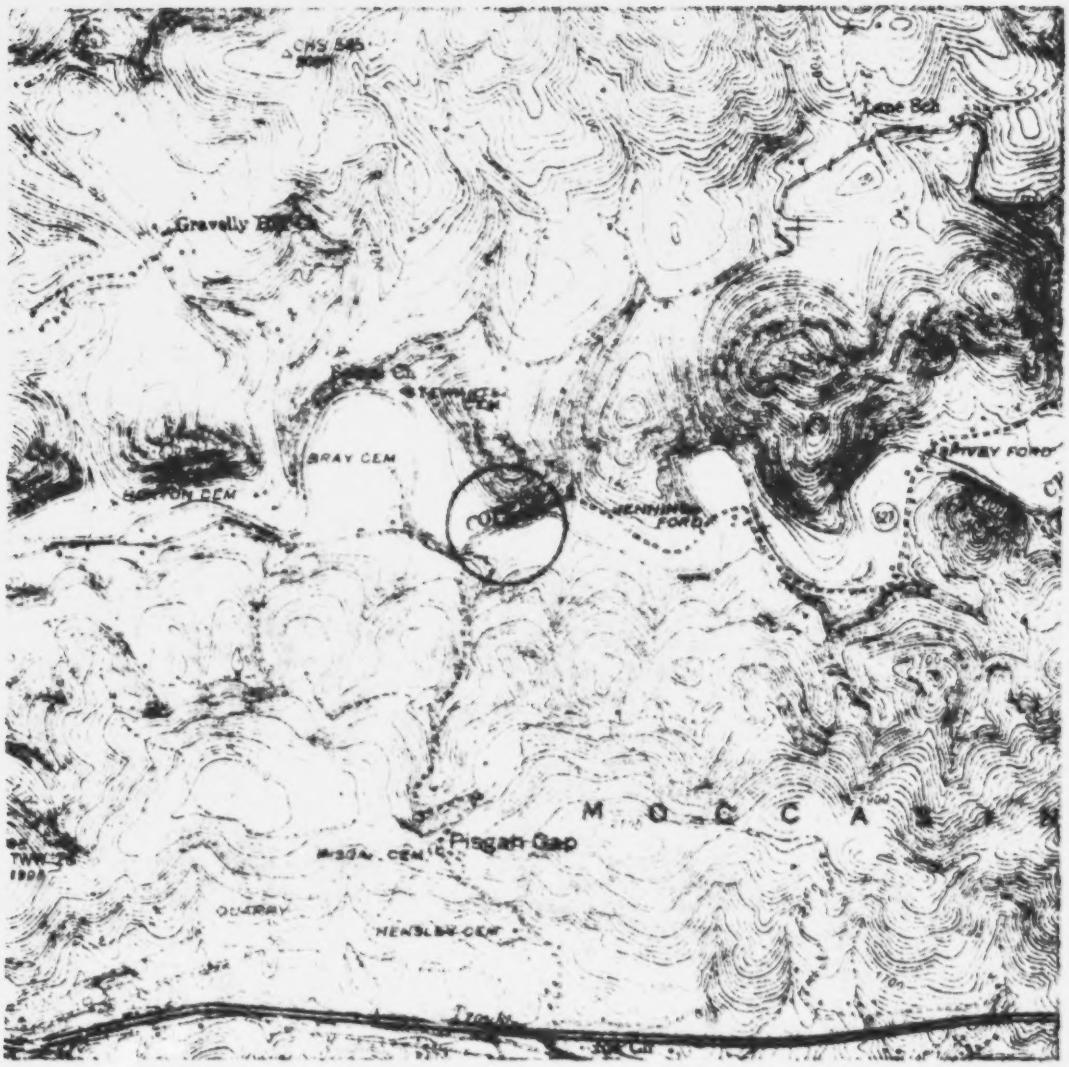

Figure 14. Topography at Copper Creek, RM 1.9 (From Quad-angle Map 188NW, Clinchport, Virginia).

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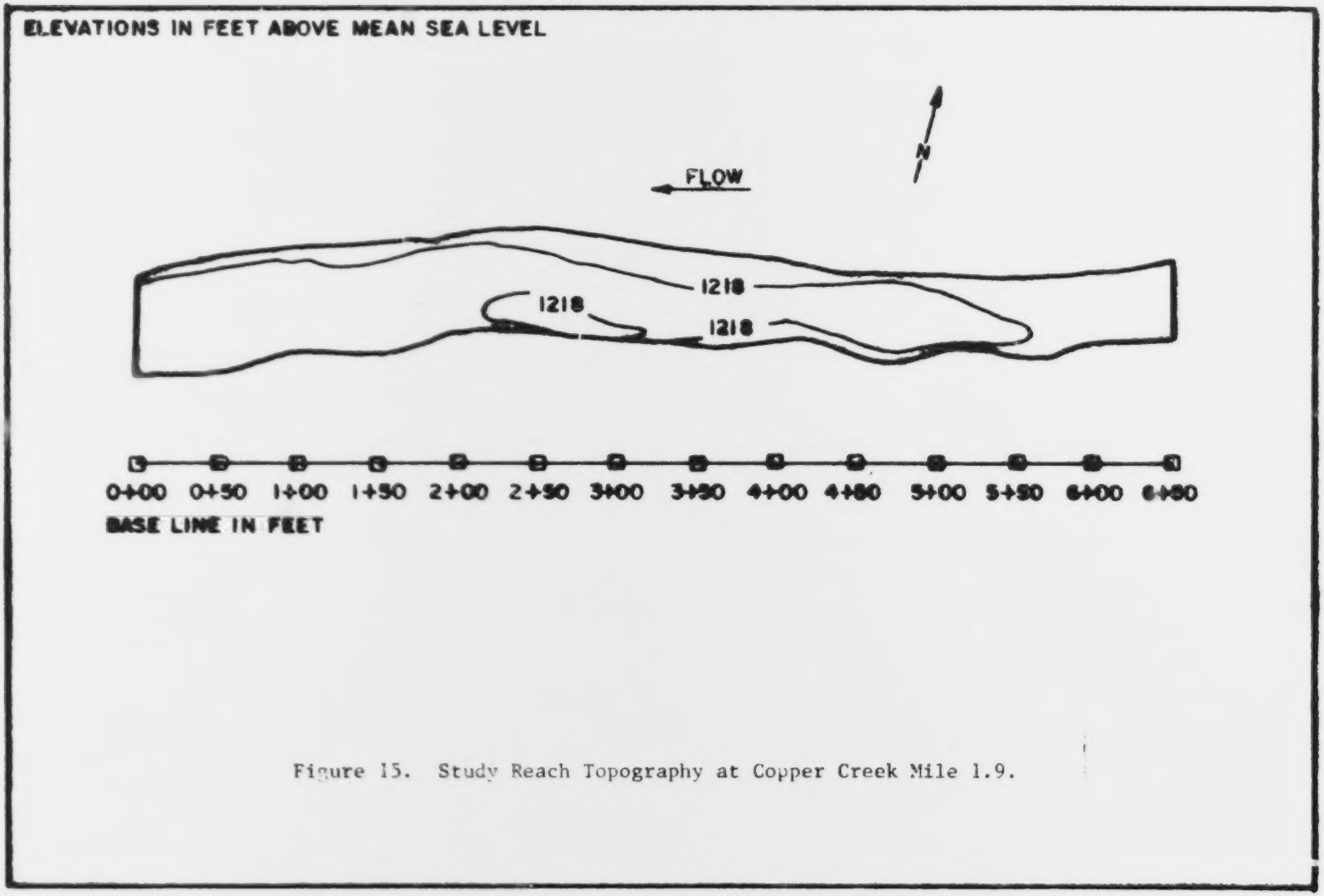

Figure 15. Study Reach Topography at Copper Creek Mile 1.9.

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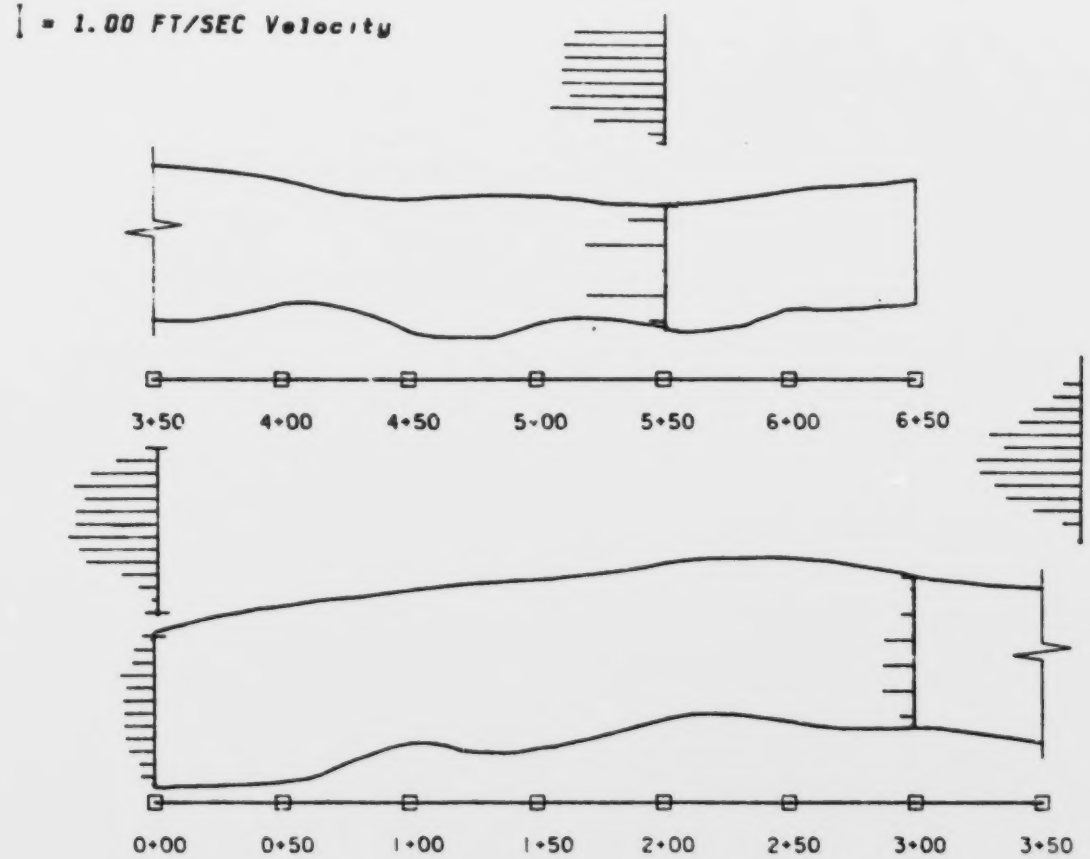

Figure 16. Low and High Measured Velocity Distributions at Copper Creek Mile 1.9.

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LEGEND:

—— = AREAS DRY DURING SAMPLED LOW-FLOW CONDITIONS

a × b = LOCATION OF SAMPLE

× = LOCATION

a = SUBSURFACE SUBSTRATE TYPE

b = SURFACE SUBSTRATE TYPE

SUBSTRATE TYPES

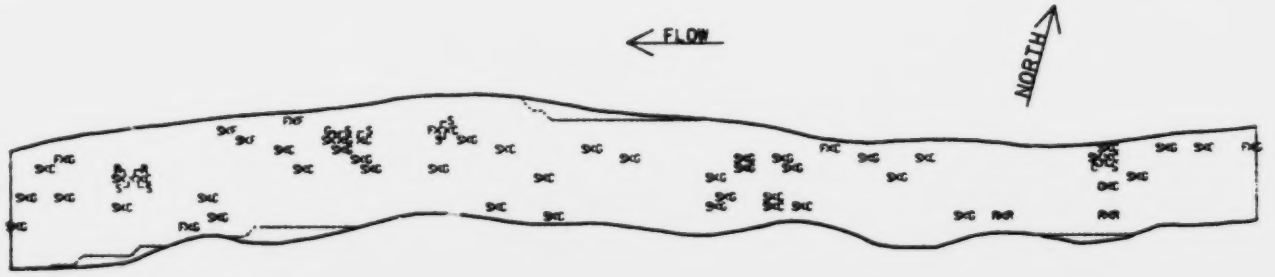
F = FINE PARTICLES (SILT AND CLAY)

S = SAND

G = GRAVEL

C = COBBLE

R = ROCK



0+00 0+50 1+00 1+50 2+00 2+50 3+00 3+50 4+00 4+50 5+00 5+50 6+00 6+50

BASE LINE IN FEET

Figure 17. Surface and Subsurface (3-inch Depth) Substrate Composition at Copper Creek Mile 1.9.

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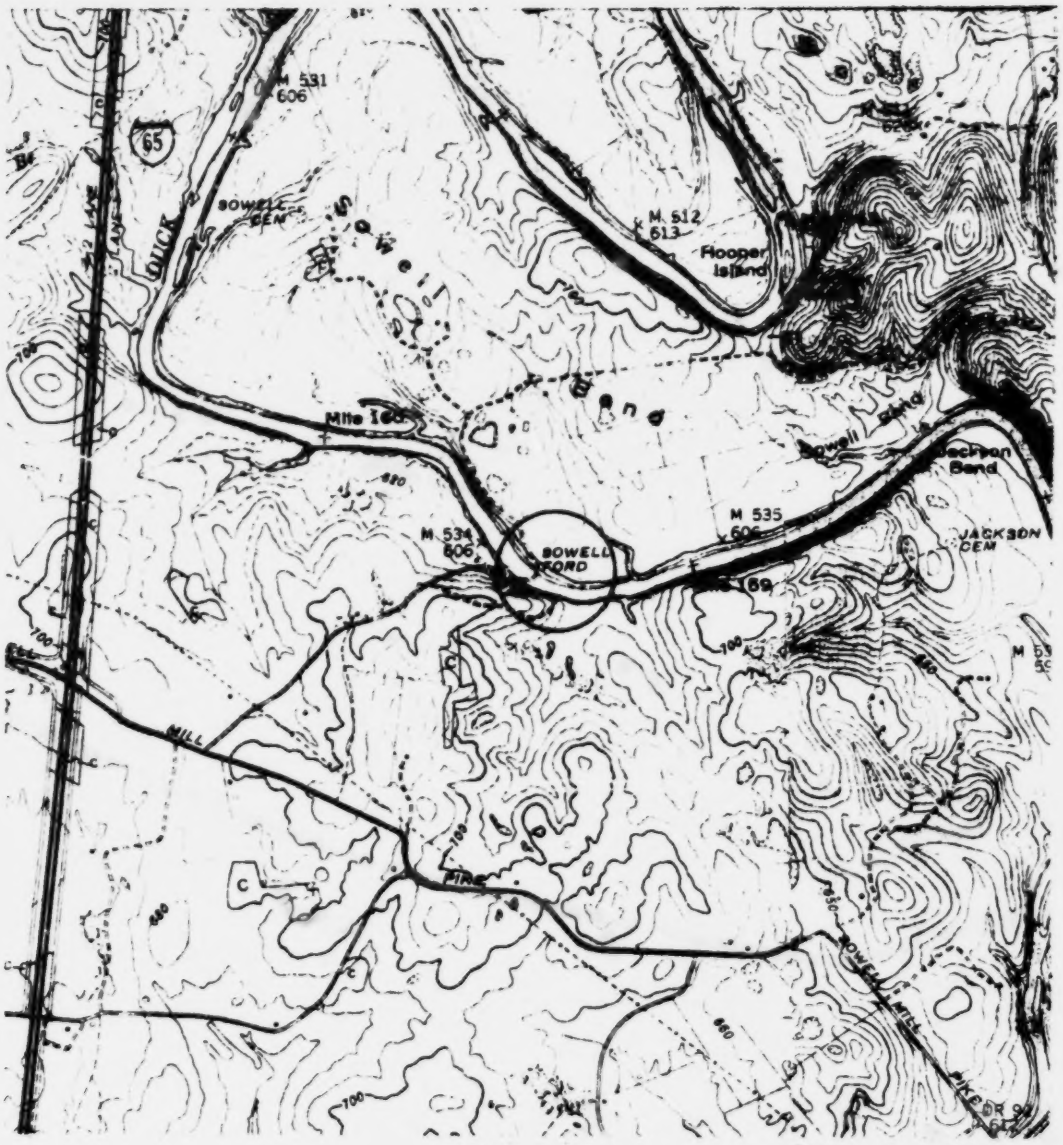

Contour interval 20 feet
Occasional 10 foot contours shown by broken lines
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Figure 18. Topography at Sowell Ford, Duck River, RM 159.4 (From Quadrangle Map 64SW, Glendale, Tennessee).

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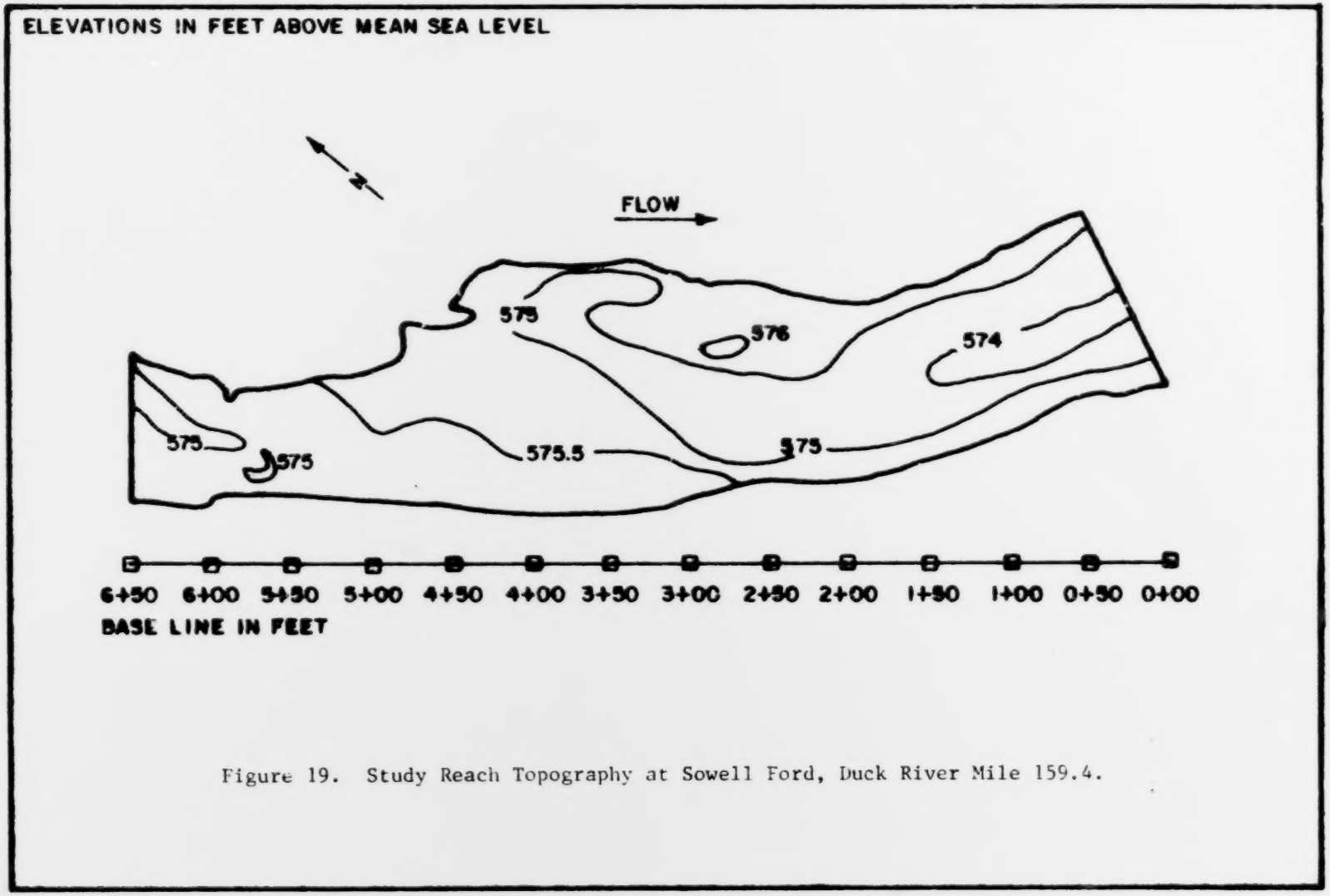

Figure 19. Study Reach Topography at Sowell Ford, Duck River Mile 159.4.

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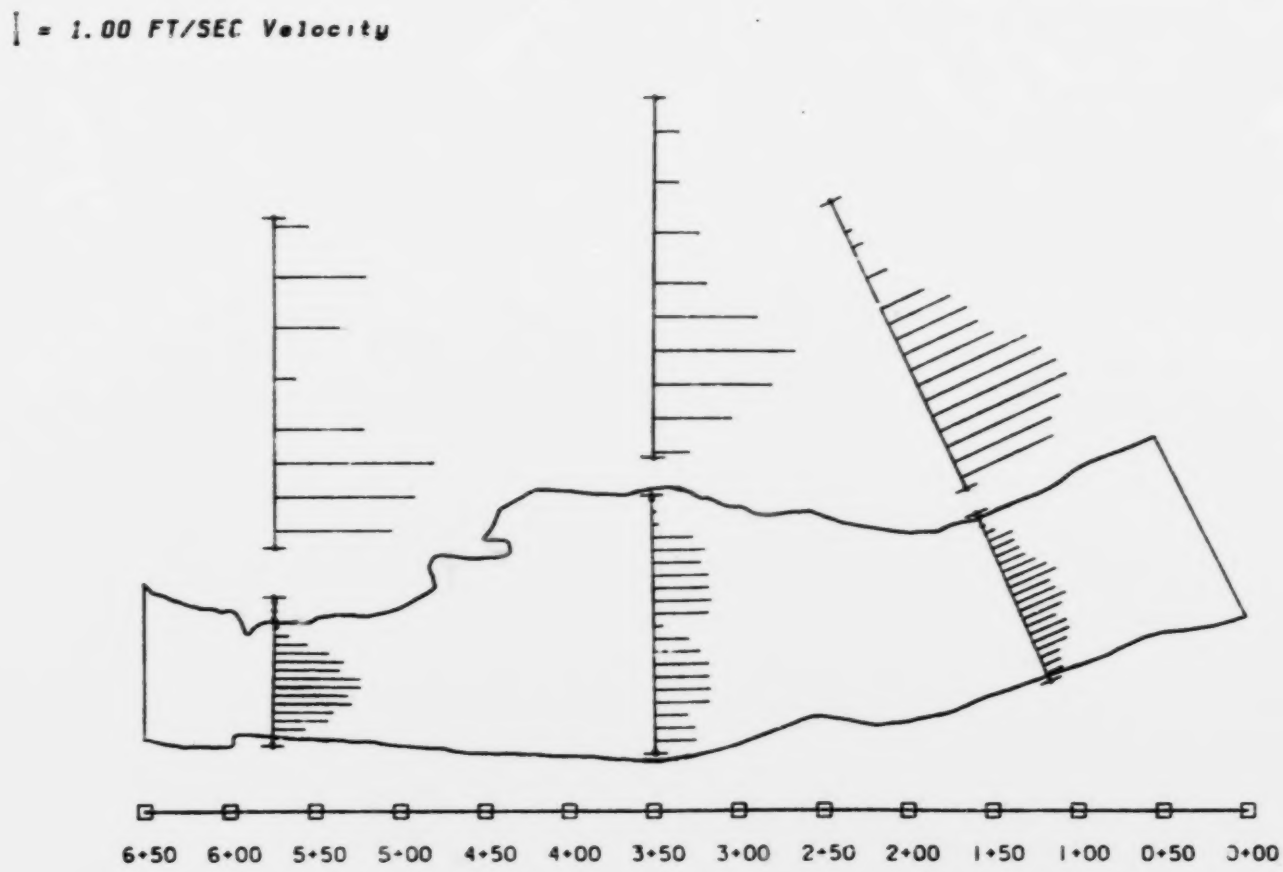

Figure 20. Low and High Measured Velocity Distributions at Sowell Ford, Duck River Mile 159.4.

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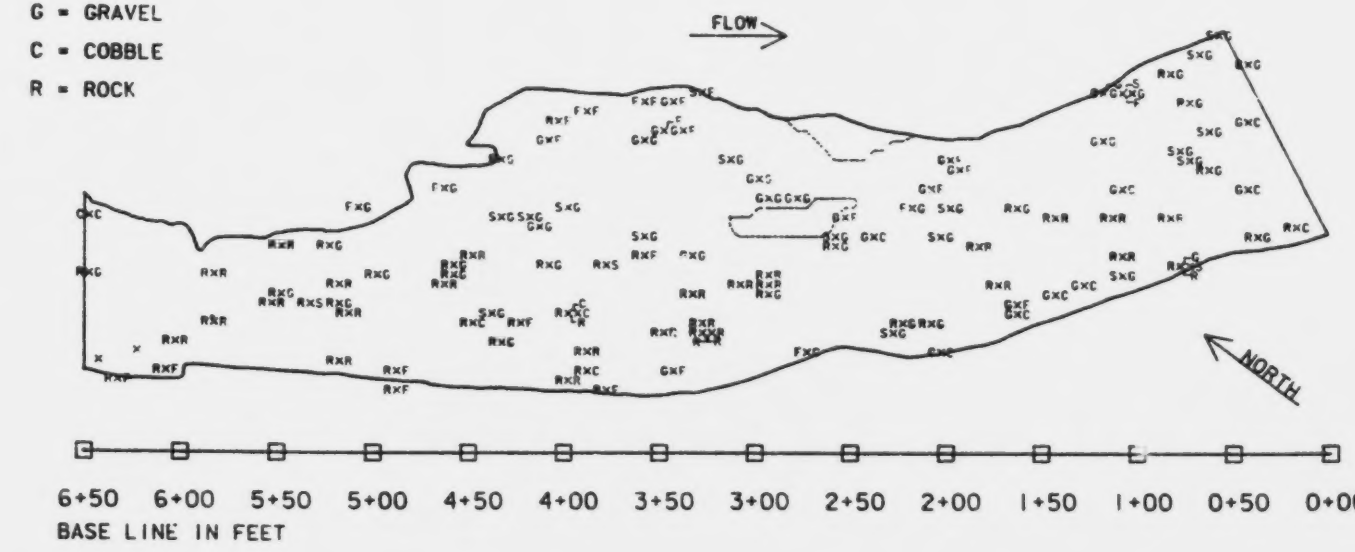
LEGEND:
—— = AREAS DRY DURING SAMPLED LOW-FLOW CONDITIONS
a × b = LOCATION OF SAMPLE
× = LOCATION
a = SUBSURFACE SUBSTRATE TYPE
b = SURFACE SUBSTRATE TYPE
SUBSTRATE TYPES
F = FINE PARTICLES (SILT AND CLAY)
S = SAND
G = GRAVEL
C = COBBLE
R = ROCK
FLOW
NORTH
6+50 6+00 5+50 5+00 4+50 4+00 3+50 3+00 2+50 2+00 1+50 1+00 0+50 0+00
BASE LINE IN FEET

Figure 21. Surface and Subsurface (3-inch Depth) Substrate Composition at Sowell Ford, Duck River Mile 159.4.

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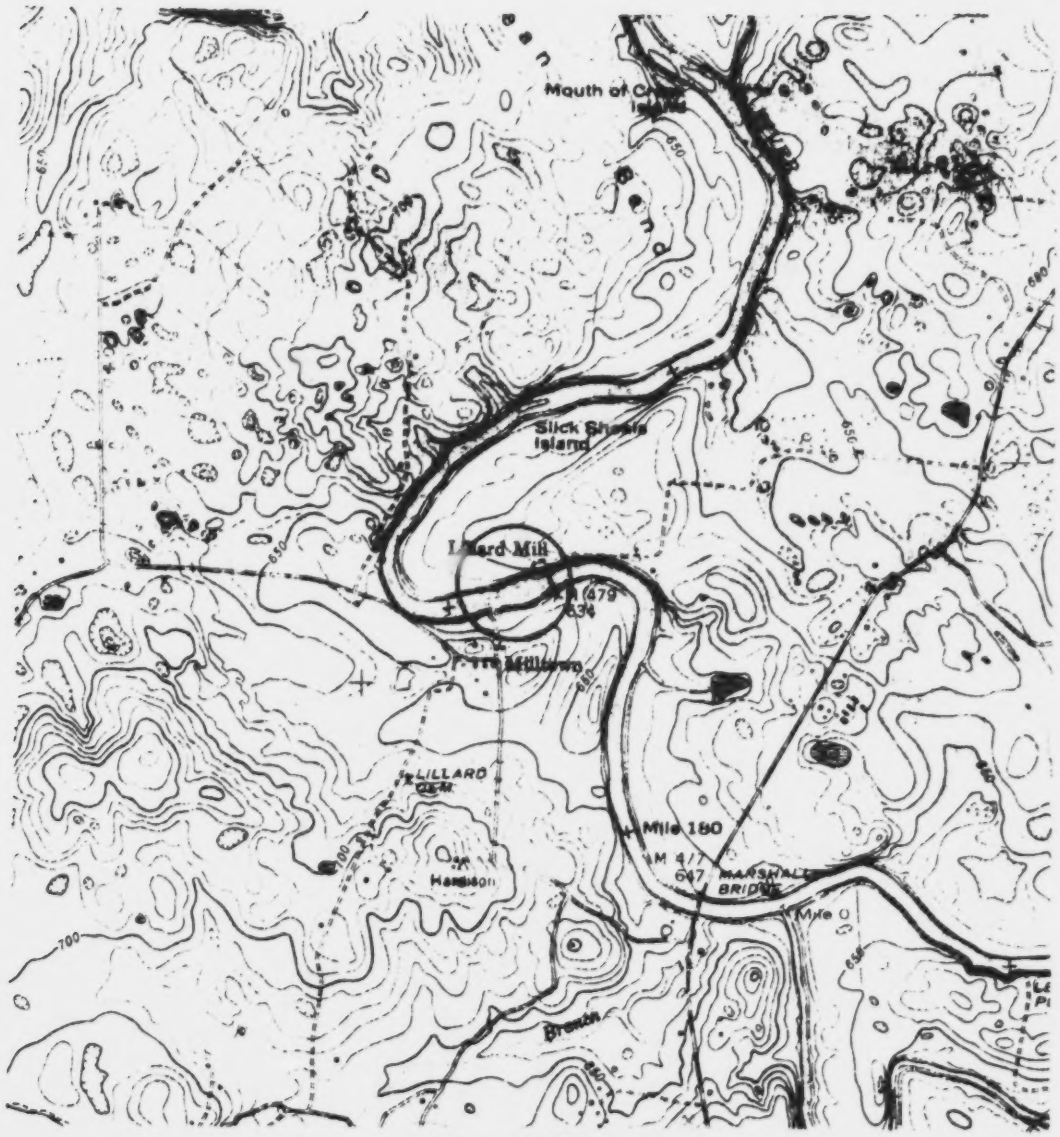

Figure 22. Topography at Lillard Mill, Duck River, RM 179.1 (From Quadrangle Map 64SE, Verona, Tennessee).

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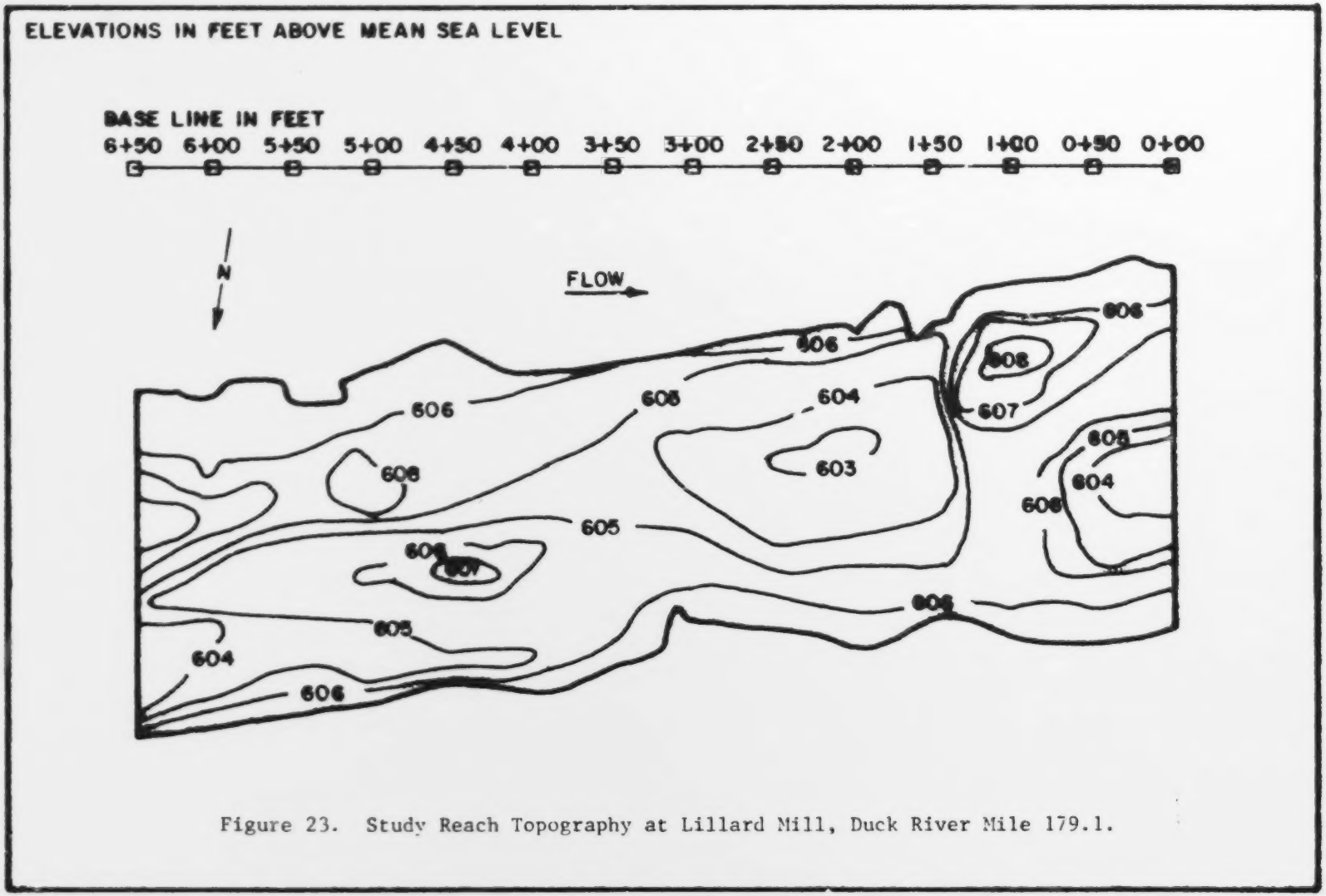

Figure 23. Study Reach Topography at Lillard Mill, Duck River Mile 179.1.

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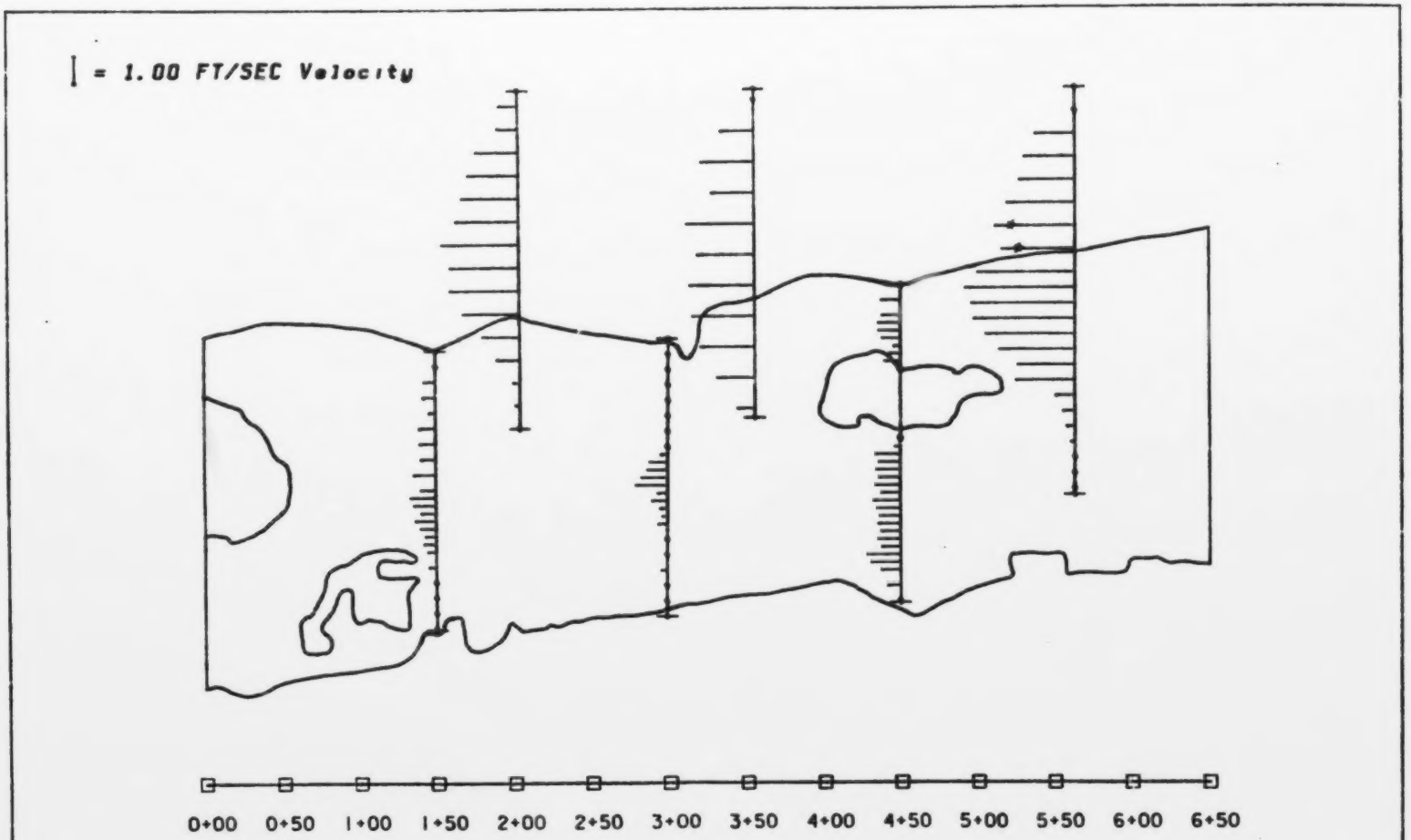

Figure 24. Low and High Measured Velocity Distributions at Lillard Mill, Duck River Mile 179.1.

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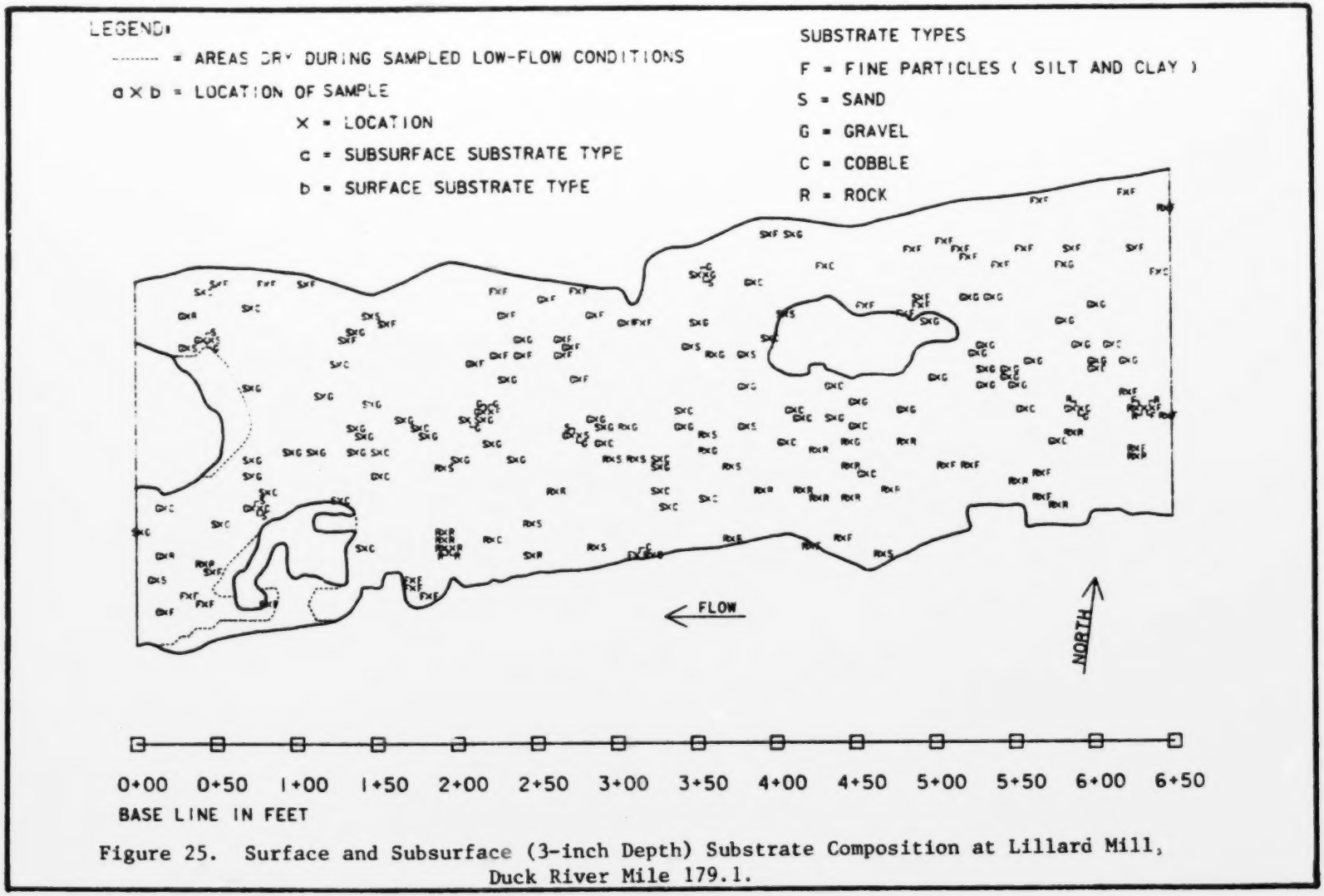
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a X b = LOCATION OF SAMPLE
X = LOCATION
c = SUBSURFACE SUBSTRATE TYPE
b = SURFACE SUBSTRATE TYPE
SUBSTRATE TYPES
F = FINE PARTICLES (SILT AND CLAY)
S = SAND
G = GRAVEL
C = COBBLE
R = ROCK
FLOW
NORTH
0+00 0+50 1+00 1+50 2+00 2+50 3+00 3+50 4+00 4+50 5+00 5+50 6+00 6+50
BASE LINE IN FEET

Figure 25. Surface and Subsurface (3-inch Depth) Substrate Composition at Lillard Mill, Duck River Mile 179.1.

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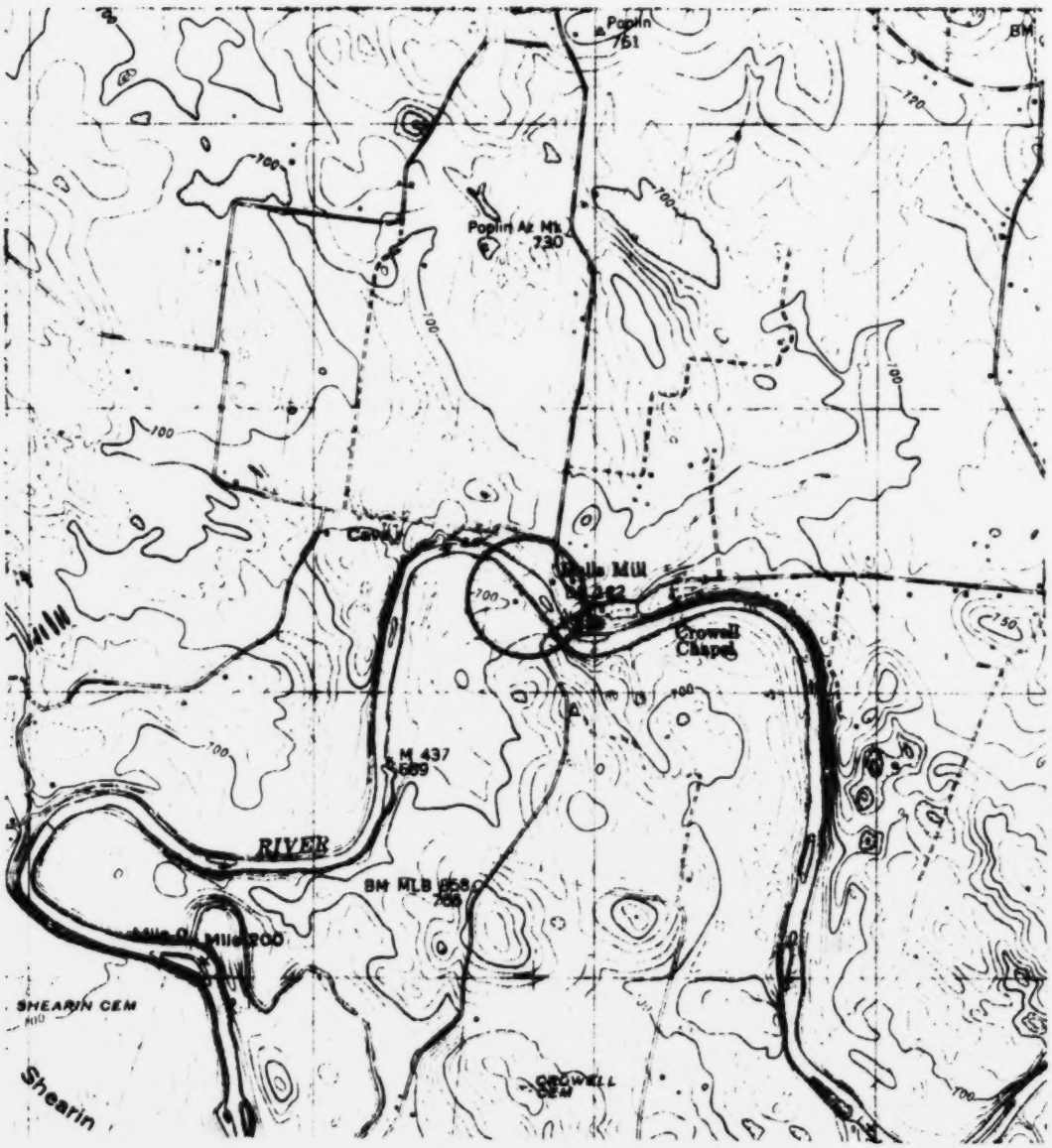

SCALE 1:24 000

1 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

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CONTOUR INTERVAL 10 FEET

DASHED LINES REPRESENT HALF INTERVAL CONTOURS

NATIONAL GEODETIC VERTICAL DATUM OF 1929

MN GN

0°15'
4 MILS

UTM GRID AND 1981 MAGNETIC NORTH
DECLINATION AT CENTER OF SHEET

Figure 26. Topography at Halls Mill, Duck River, RM 202.2 (From Quadrangle Map 71SE, Unionville, Tennessee).

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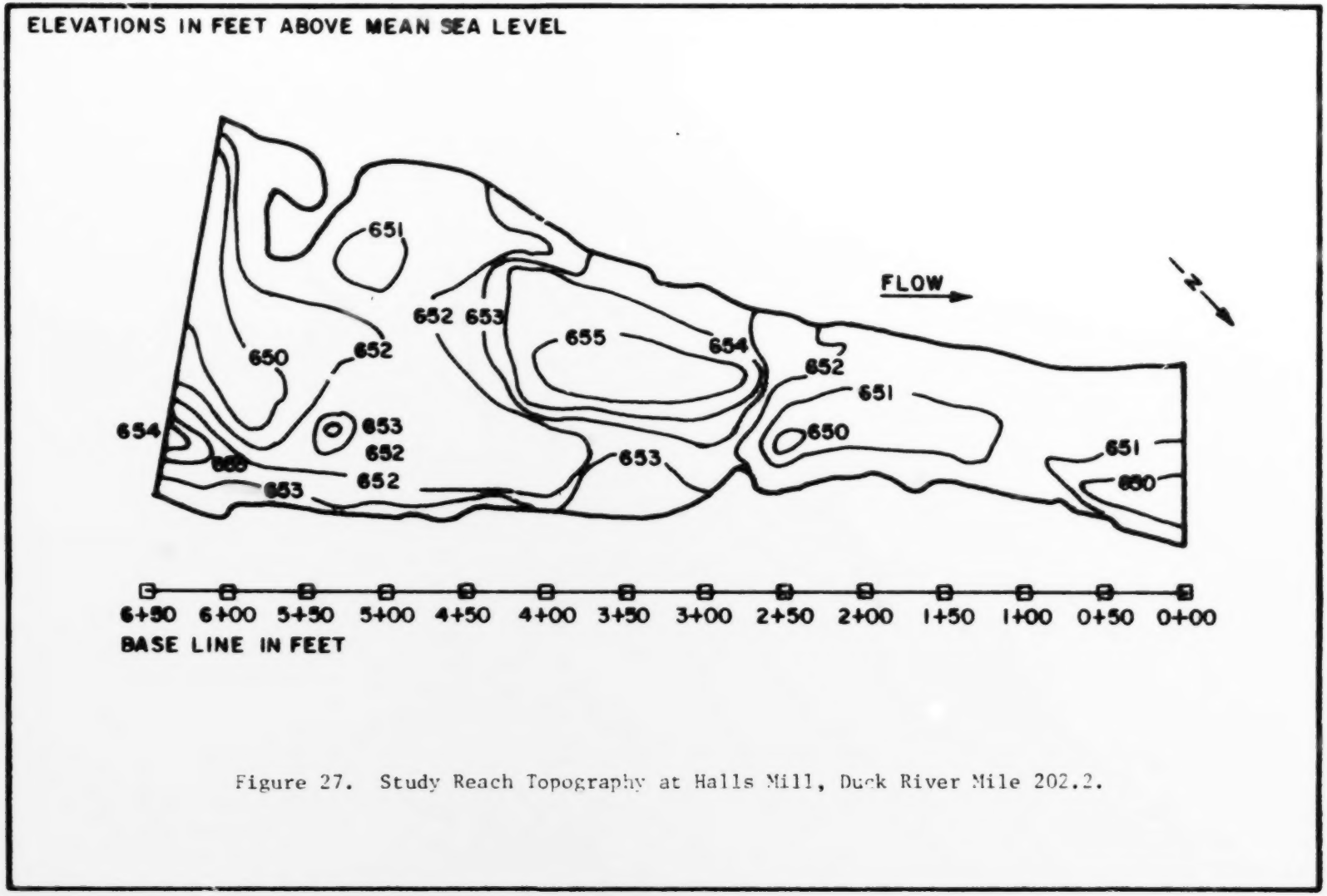

Figure 27. Study Reach Topography at Halls Mill, Duck River Mile 202.2.

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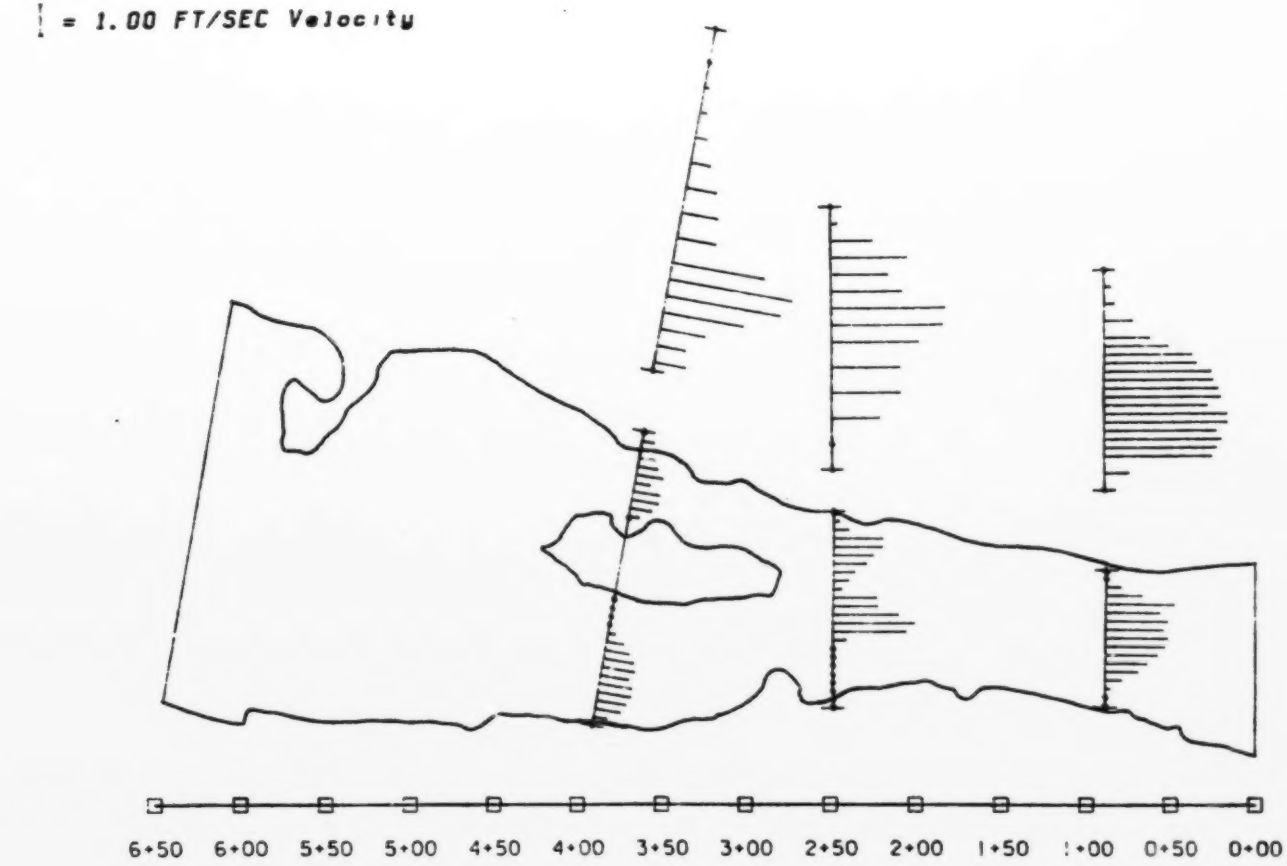

Figure 28. Low and High Measured Velocity Distributions at Halls Mill, Duck River Mile 202.2.

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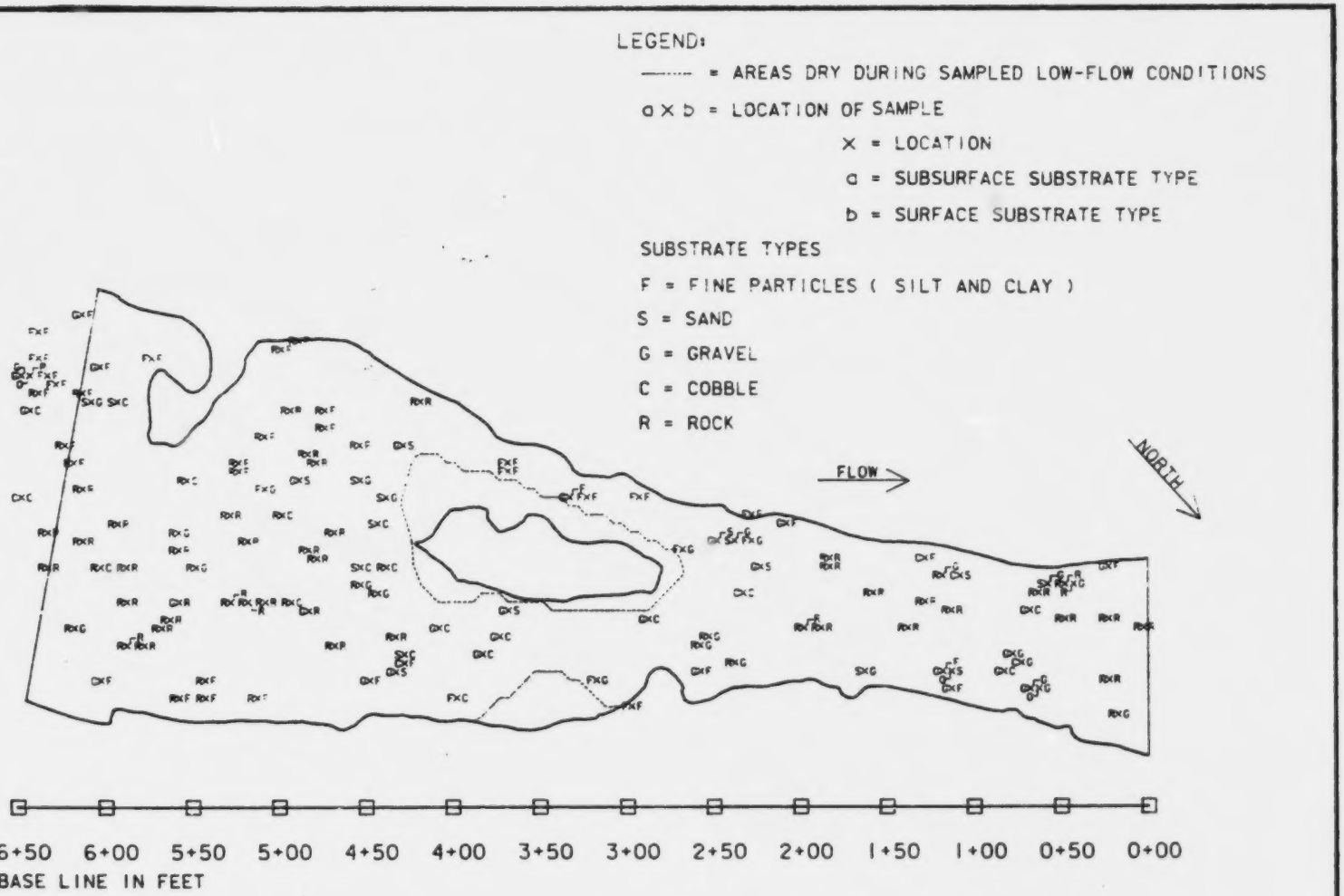
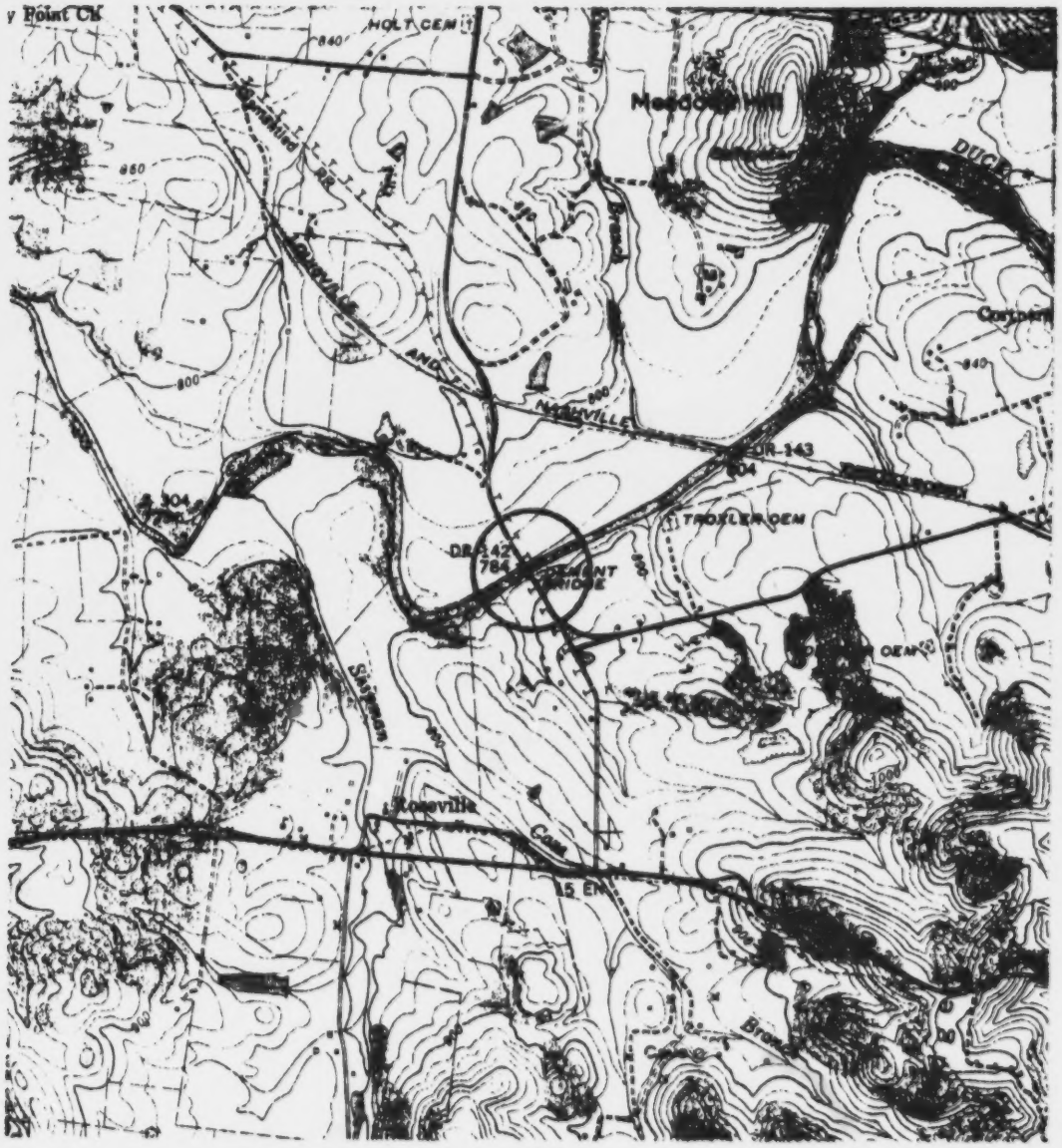

LEGEND:
——— = AREAS DRY DURING SAMPLED LOW-FLOW CONDITIONS
a X b = LOCATION OF SAMPLE
X = LOCATION
a = SUBSURFACE SUBSTRATE TYPE
b = SURFACE SUBSTRATE TYPE
SUBSTRATE TYPES
F = FINE PARTICLES (SILT AND CLAY)
S = SAND
G = GRAVEL
C = COBBLE
R = ROCK
FLOW
NORTH
6+50 6+00 5+50 5+00 4+50 4+00 3+50 3+00 2+50 2+00 1+50 1+00 0+50 0+00
BASE LINE IN FEET

Figure 29. Surface and Subsurface (3-inch Depth) Substrate Composition at Halls Mill, Duck River Mile 202.2.

BEST COPY AVAILABLE



SCALE 1:24000

1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 KILOMETER

Contour interval 20 feet

Datum is mean sea level

2°

TRUE NORTH

MAGNETIC NORTH

APPROXIMATE MEAN DECLINATION, 1987

Figure 30. Topography at Dement Bridge, Duck River Mile 243.1 (From Quadrangle Map 79NE, Normandy, Tennessee).

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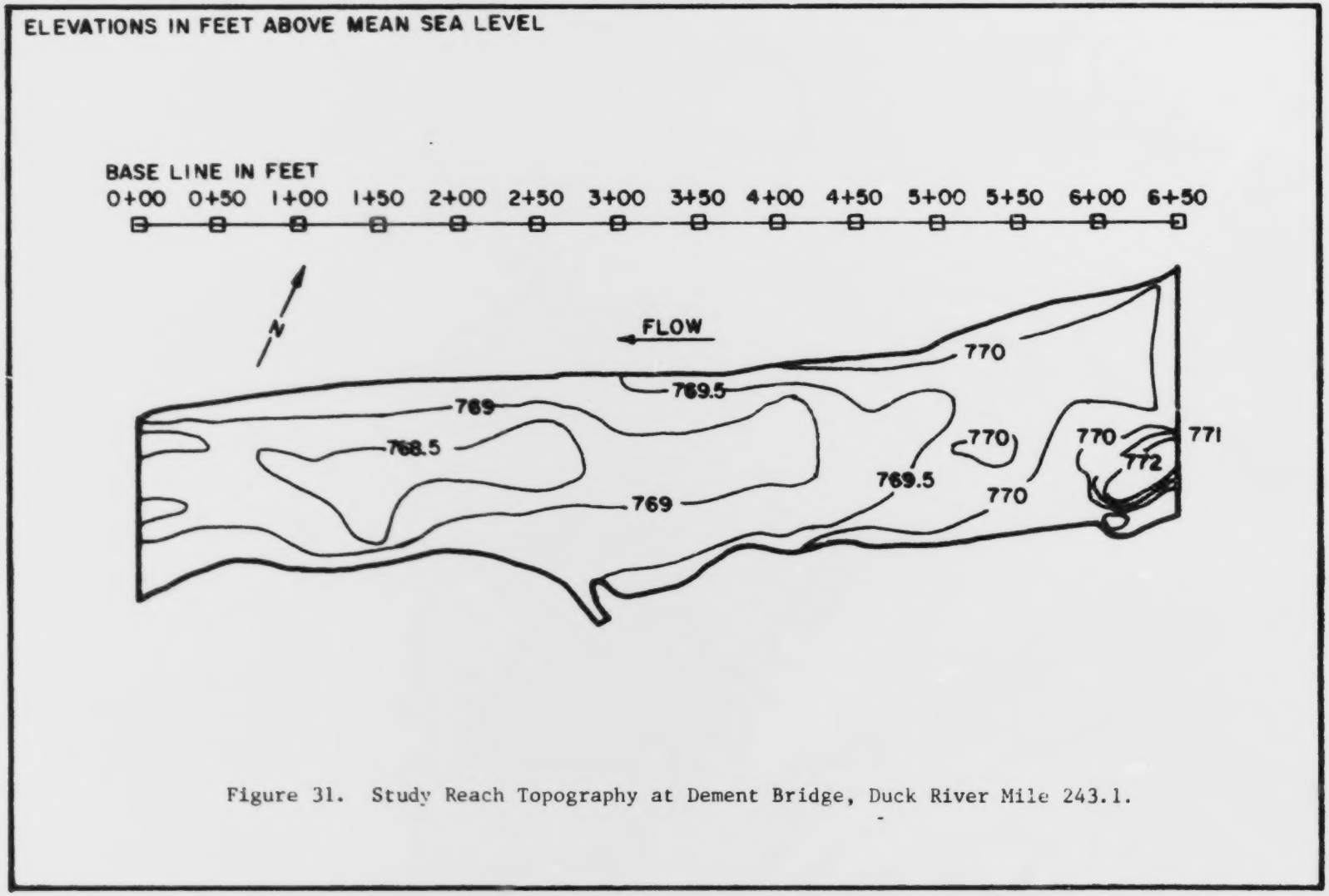

Figure 31. Study Reach Topography at Dement Bridge, Duck River Mile 243.1.

BEST COPY AVAILABLE

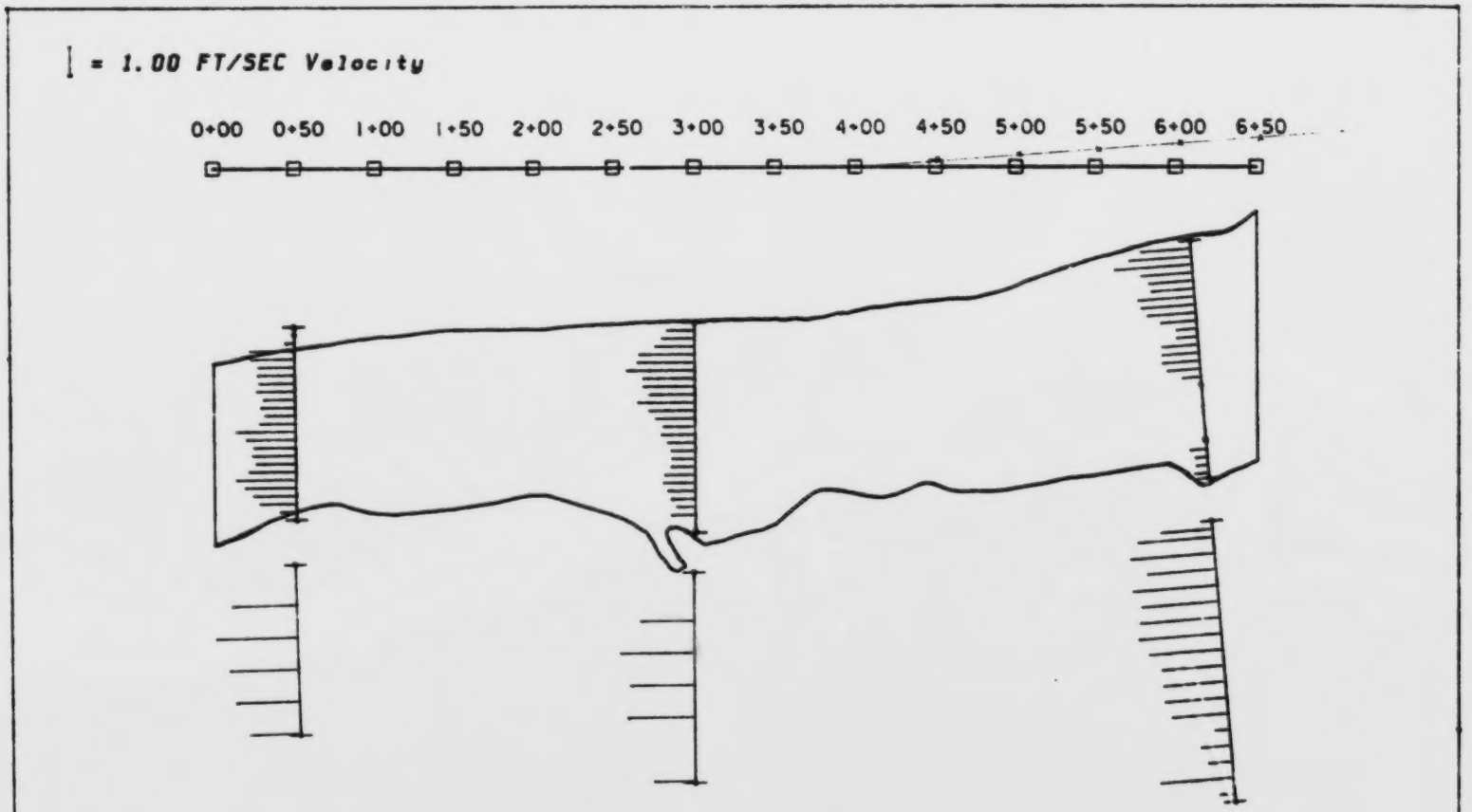

Figure 32. Low and High Measured Velocity Distributions at Dement Bridge, Duck River Mile 243.1.

BEST COPY AVAILABLE

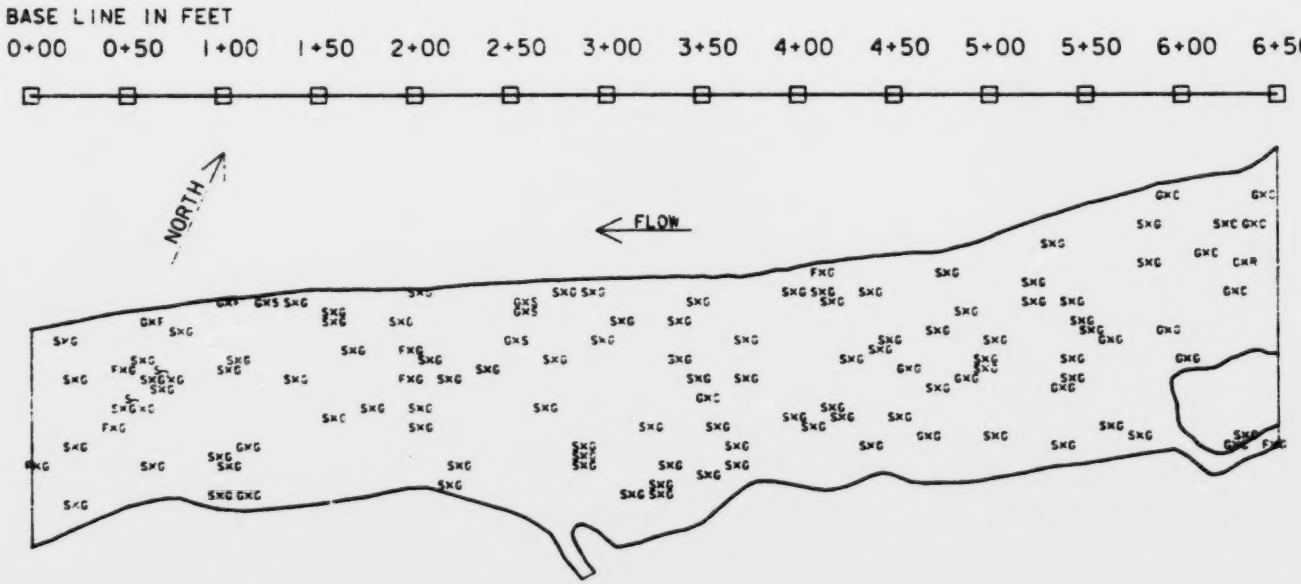
BASE LINE IN FEET
0+00 0+50 1+00 1+50 2+00 2+50 3+00 3+50 4+00 4+50 5+00 5+50 6+00 6+50
NORTH
FLOW
LEGEND:
—— = AREAS DRY DURING SAMPLED LOW-FLOW CONDITIONS
aX b = LOCATION OF SAMPLE
X = LOCATION
a = SUBSURFACE SUBSTRATE TYPE
b = SURFACE SUBSTRATE TYPE
SUBSTRATE TYPES
F = FINE PARTICLES (SILT AND CLAY)
S = SAND
G = GRAVEL
C = COBBLE
R = ROCK

Figure 33. Surface and Subsurface (3-inch Depth) Substrate Composition at Dement Bridge, Duck River Mile 243.1.

BEST COPY AVAILABLE

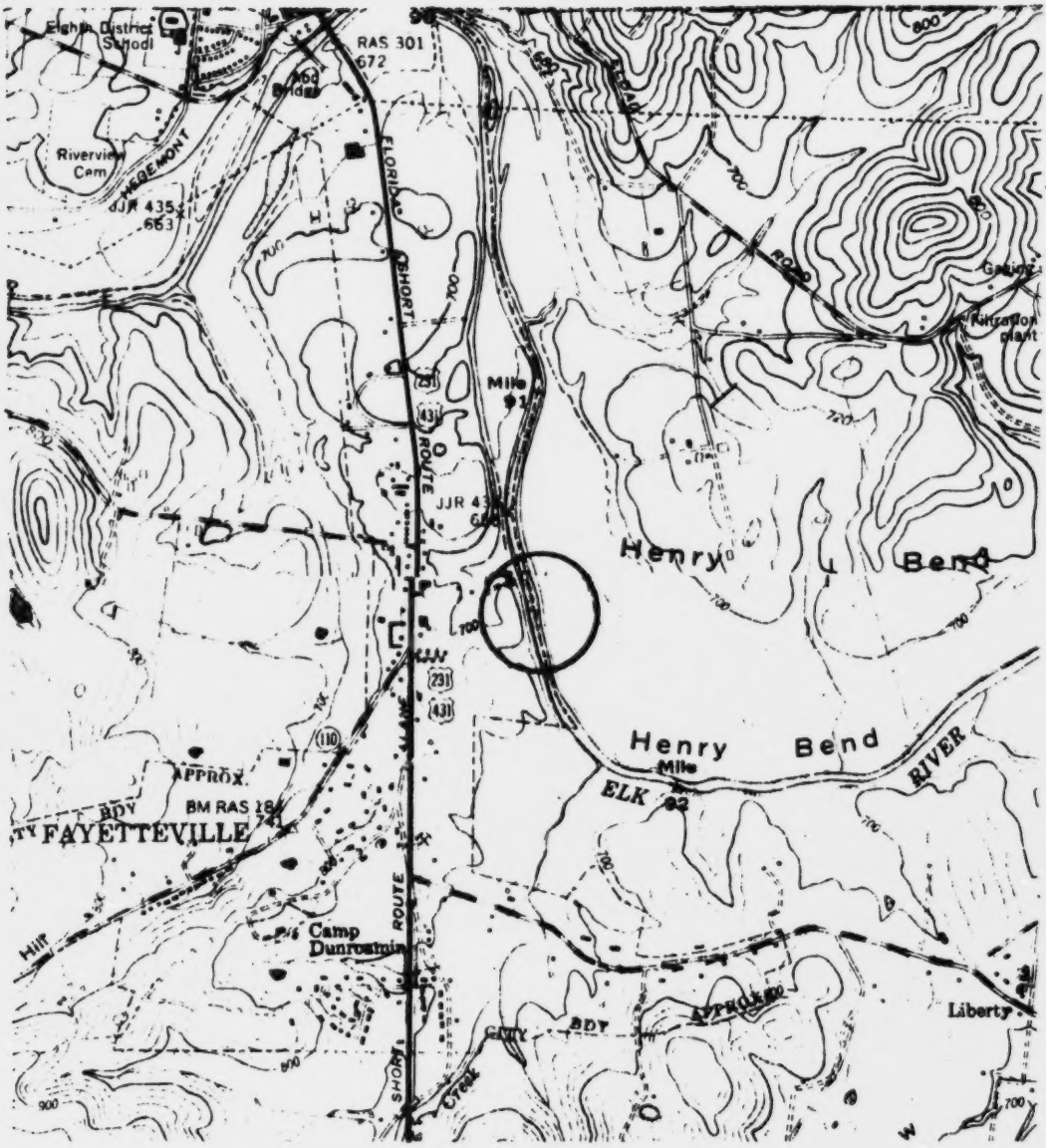

Figure 34. Topography at Elk River, RM 91.4 (From Quadrangle Maps 73NE, Fayetteville, Tennessee, and 73SE, Lincoln, Tennessee).

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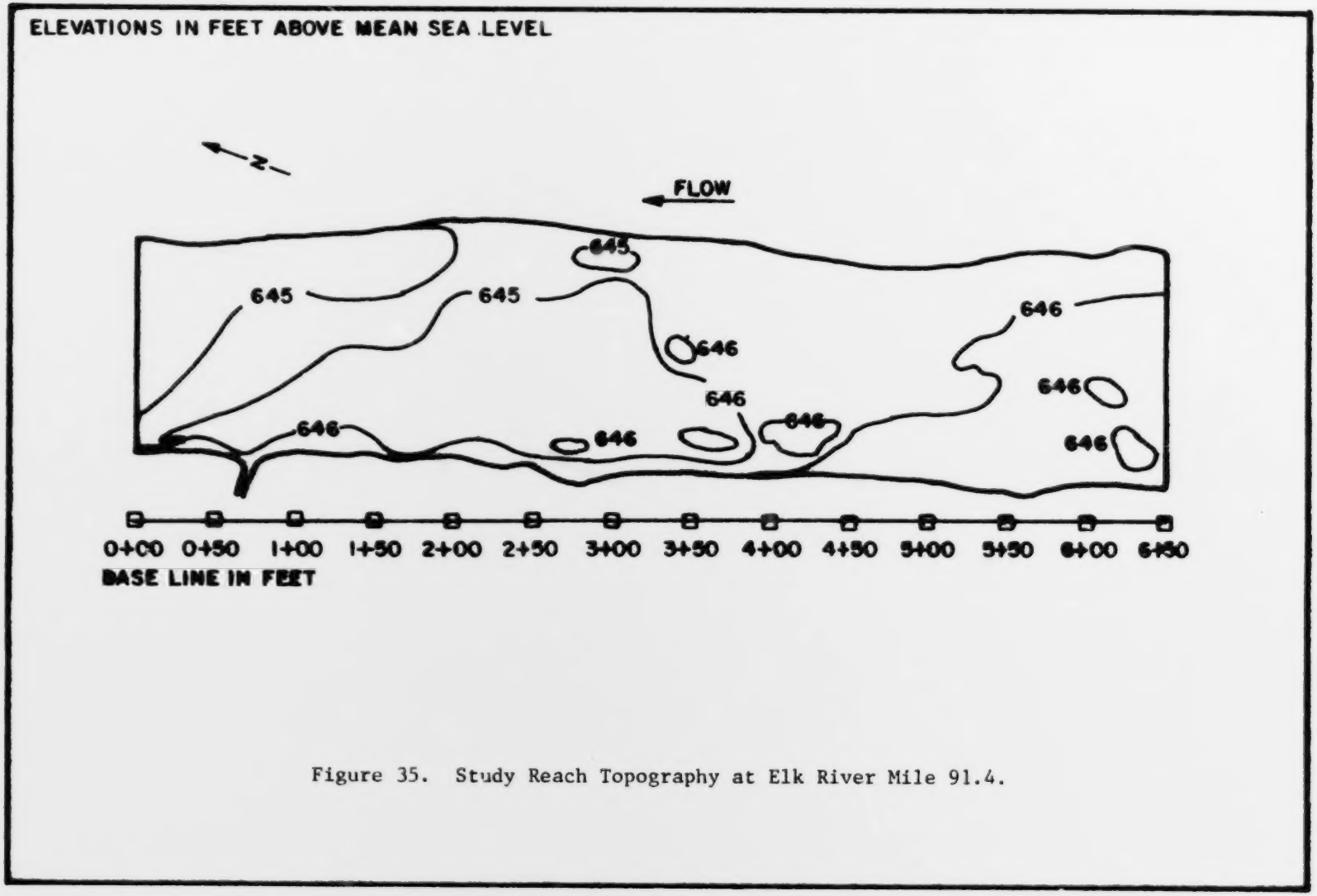


Figure 35. Study Reach Topography at Elk River Mile 91.4.

BEST COPY AVAILABLE

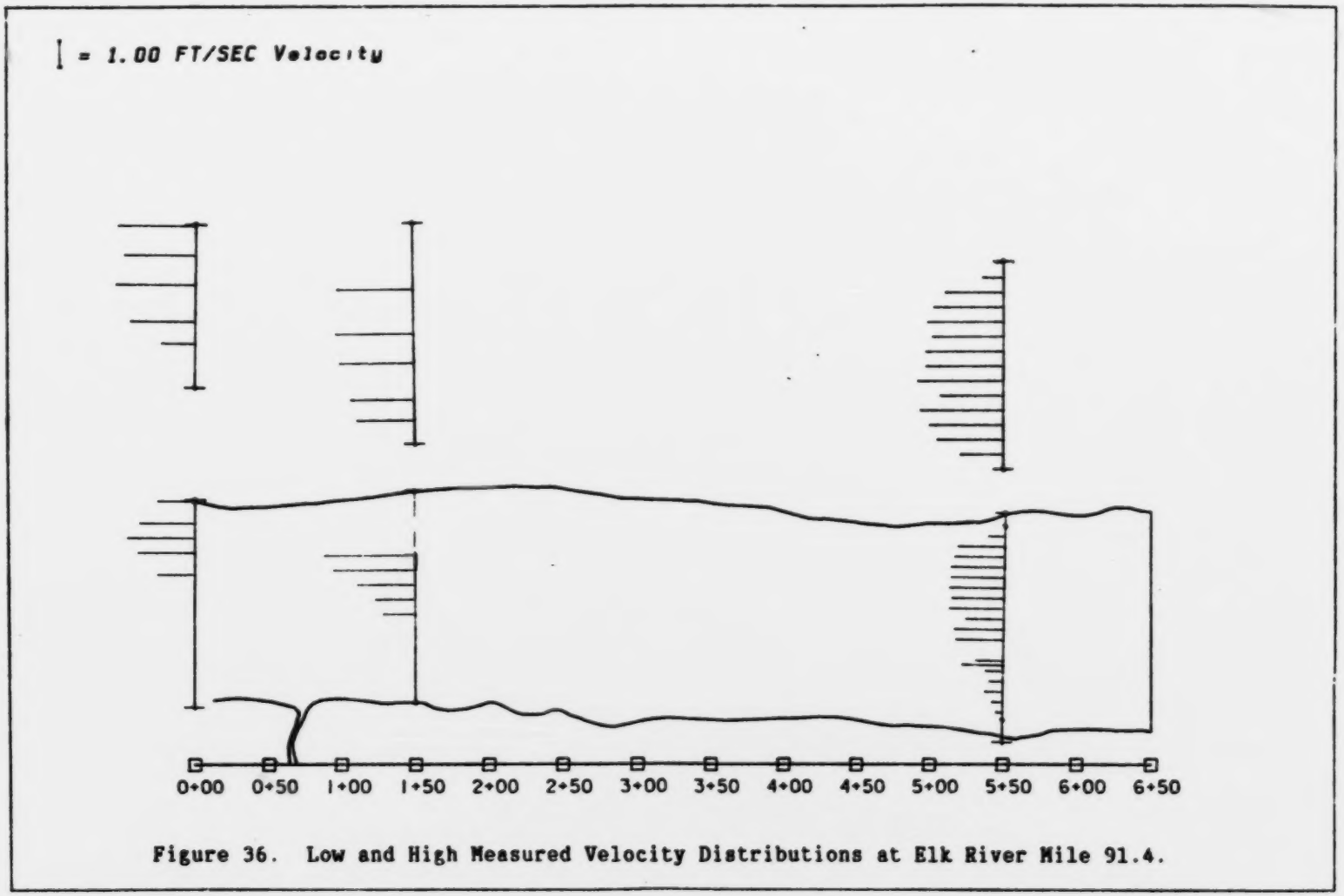


Figure 36. Low and High Measured Velocity Distributions at Elk River Mile 91.4.

BEST COPY AVAILABLE

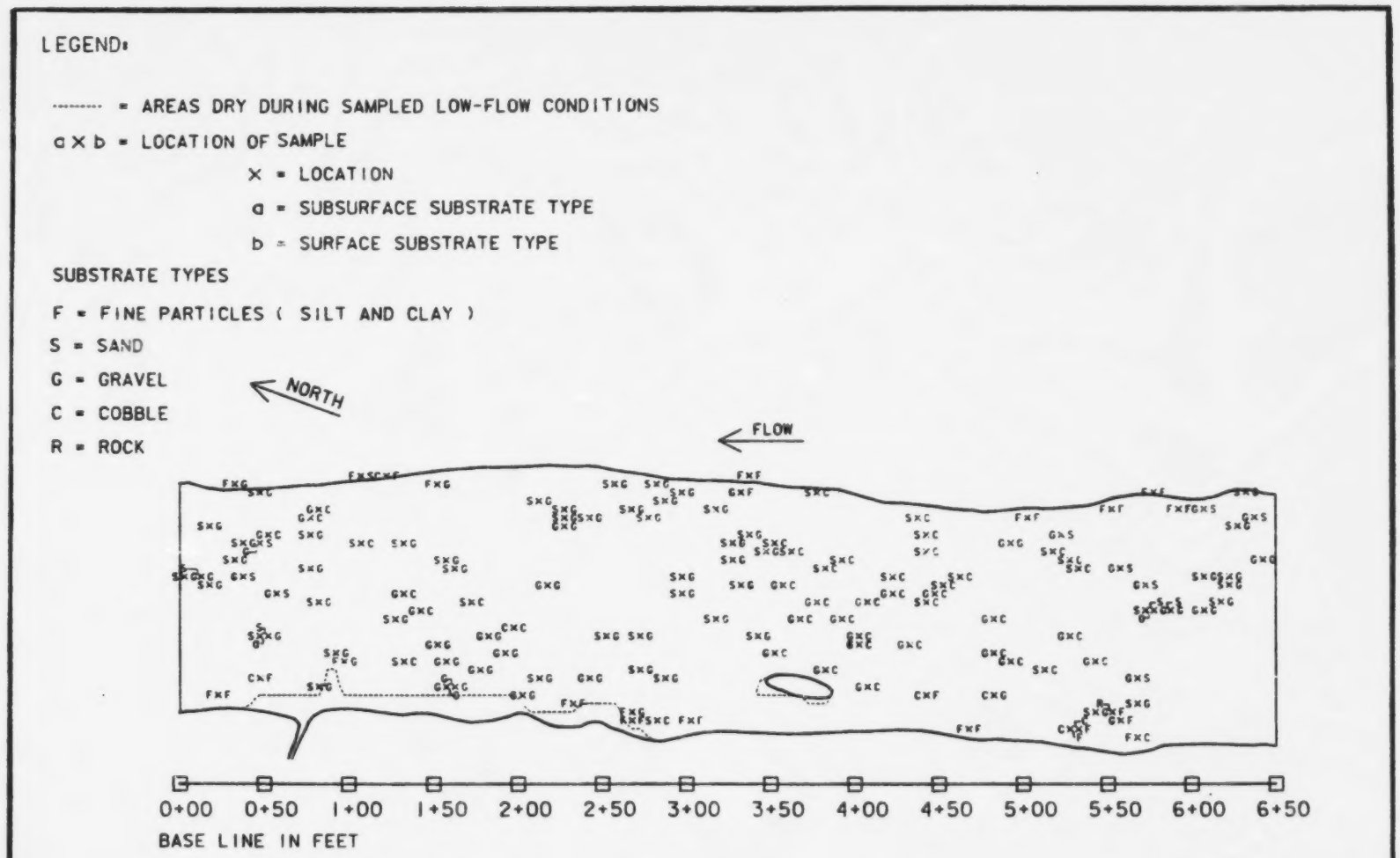


Figure 37. Surface and Subsurface (3-inch Depth) Substrate Composition at Elk River Mile 91.4.

BEST COPY AVAILABLE

SCALE 1:24000

1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 KILOMETER

CONTOUR INTERVAL 20 FEET
DASHED LINES REPRESENT HALF-INTERVAL CONTOURS
DATUM IS MEAN SEA LEVEL

MN
GN
2°
36 MILS
1°13'
22MILS

UTM GRID AND 1971 MAGNETIC NORTH
DECLINATION AT CENTER OF SHEET

Figure 38. Topography at Hale Bridge, Nolichucky River, RM 27.8 (From Quadrangle Map 172SE, Parrottsville, Tennessee).

BEST COPY AVAILABLE

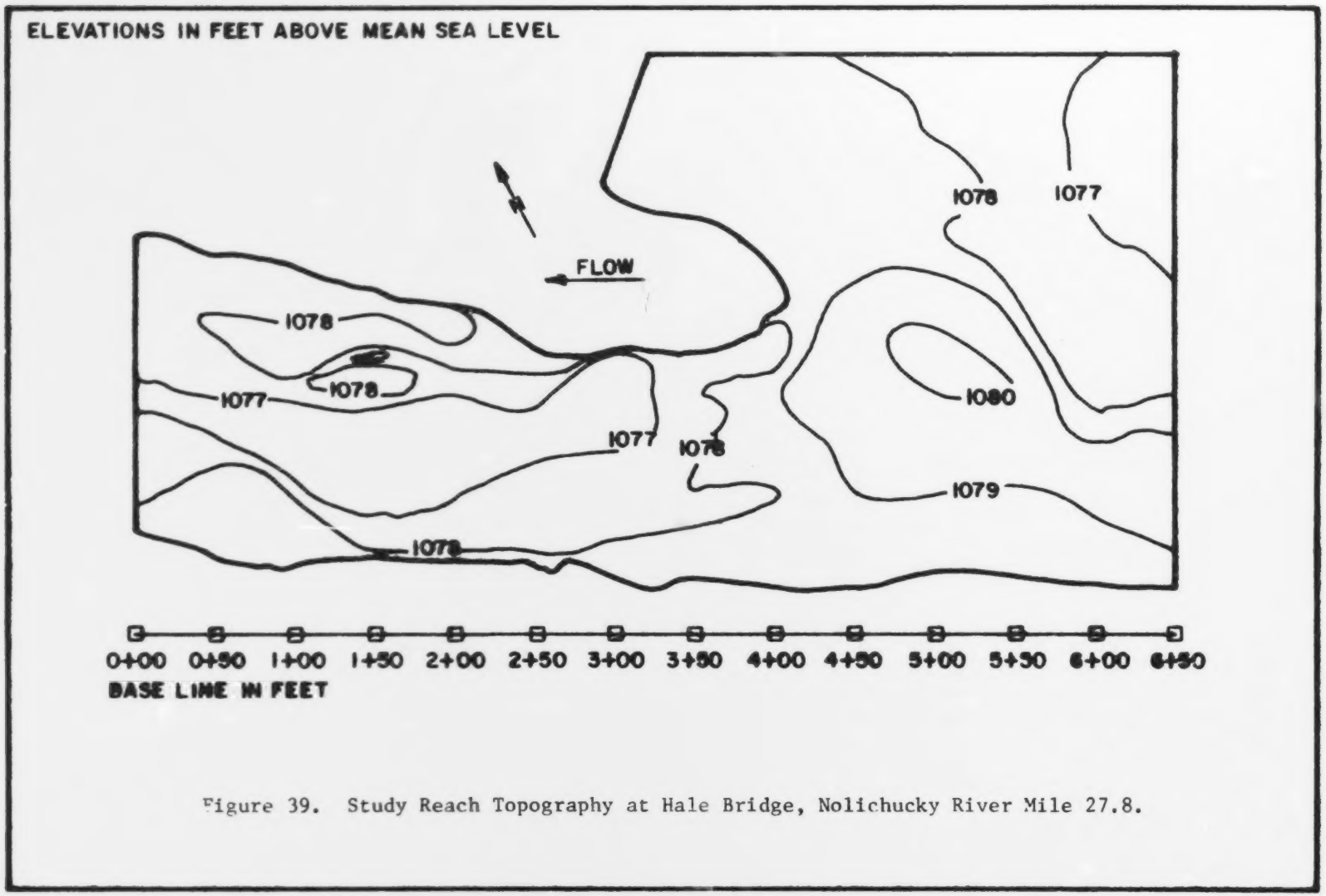


Figure 39. Study Reach Topography at Hale Bridge, Nolichucky River Mile 27.8.

BEST COPY AVAILABLE

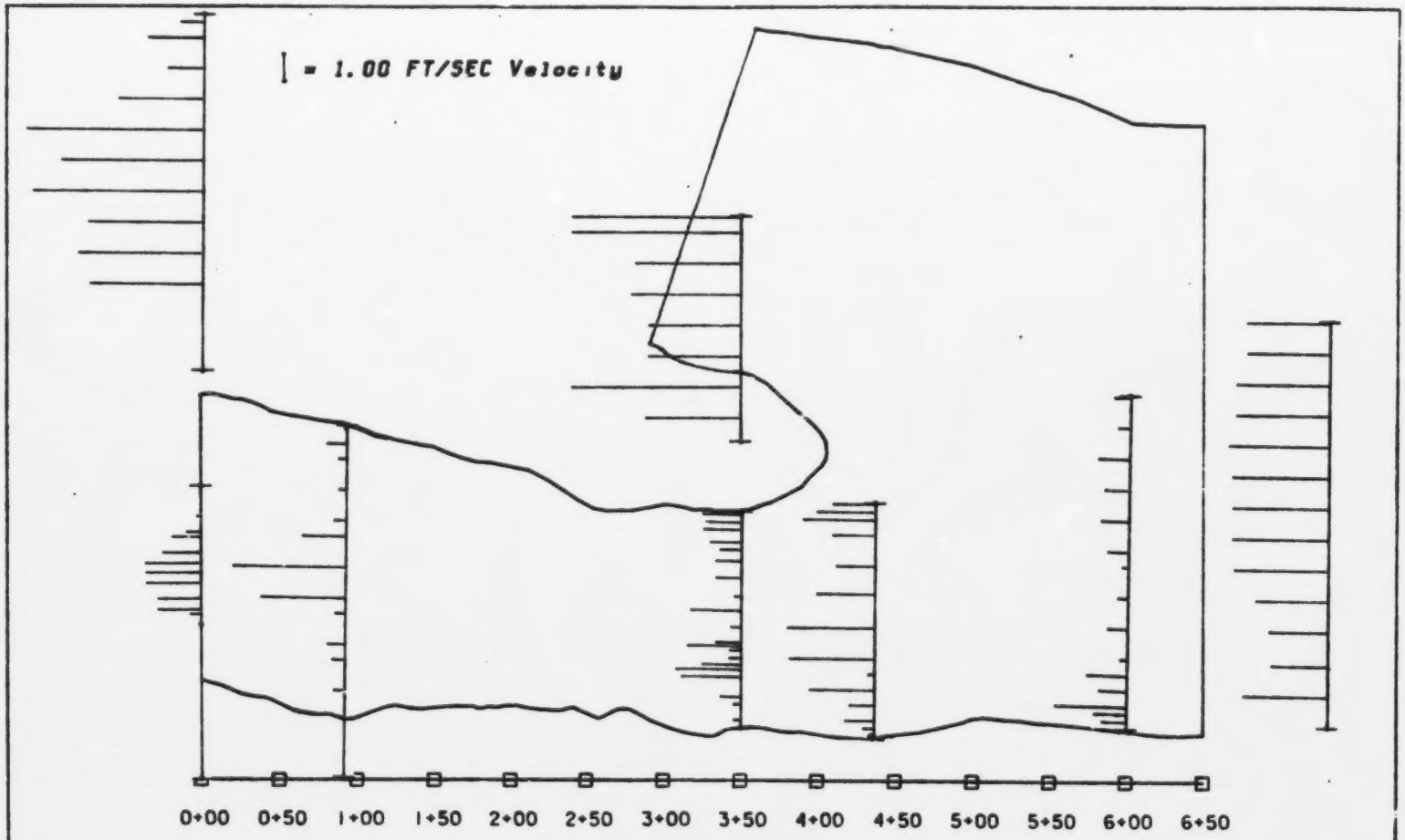
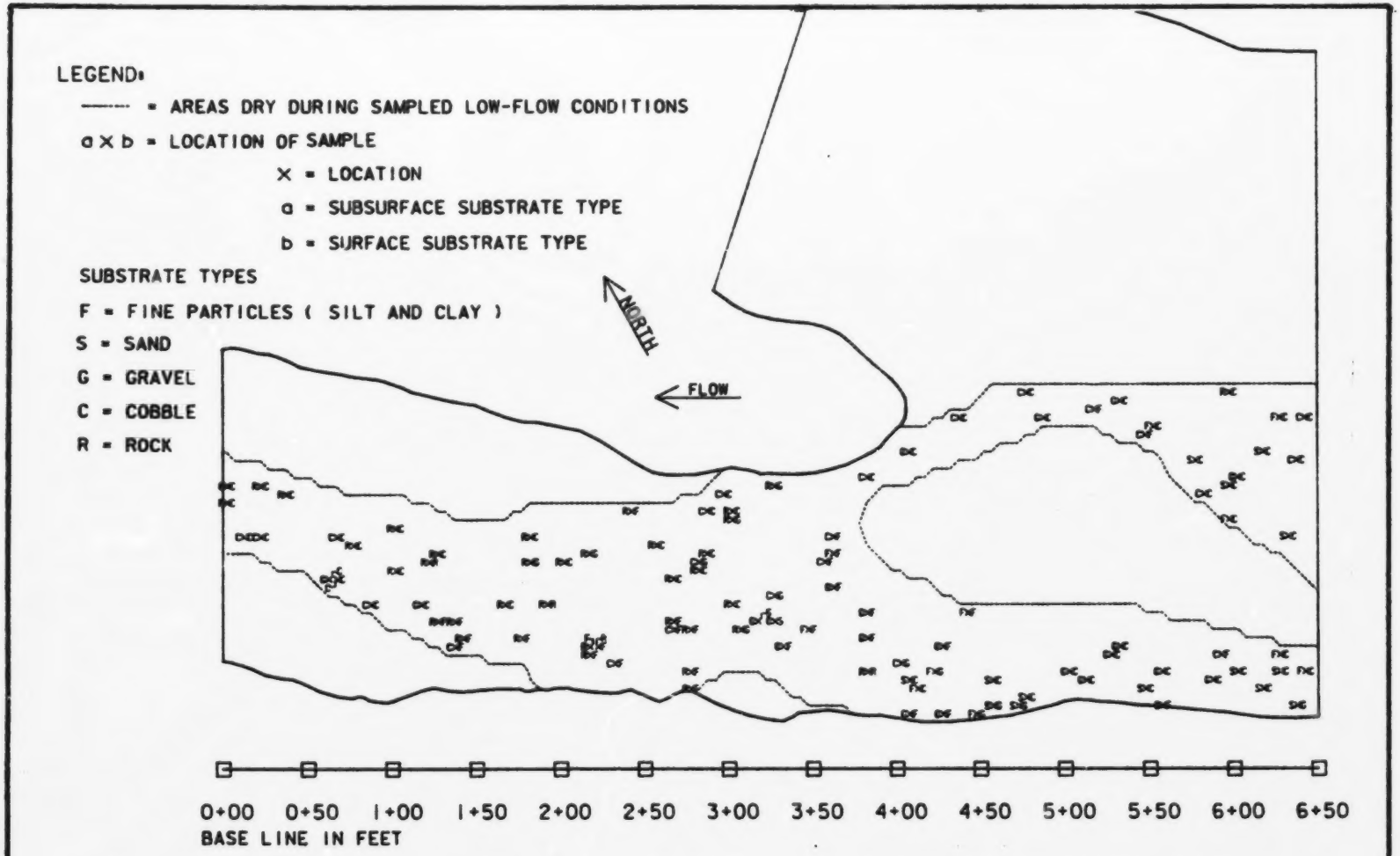


Figure 40. Low and High Measured Velocity Distributions at Hale Bridge, Nolichucky River Mile 27.8.

BEST COPY AVAILABLE


LEGEND:
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a × b = LOCATION OF SAMPLE
× = LOCATION
a = SUBSURFACE SUBSTRATE TYPE
b = SURFACE SUBSTRATE TYPE
SUBSTRATE TYPES
F = FINE PARTICLES (SILT AND CLAY)
S = SAND
G = GRAVEL
C = COBBLE
R = ROCK
NORTH
FLOW
0+00 0+50 1+00 1+50 2+00 2+50 3+00 3+50 4+00 4+50 5+00 5+50 6+00 6+50
BASE LINE IN FEET

Figure 41. Surface and Subsurface (3-inch Depth) Substrate Composition at Nolichucky River Mile 27.8.

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Figure 42. Topography at Click Island, N. Fork Holston River, RM 6.2 (From Quadrangle Map 188SE, Kingsport, Tennessee-Virginia).

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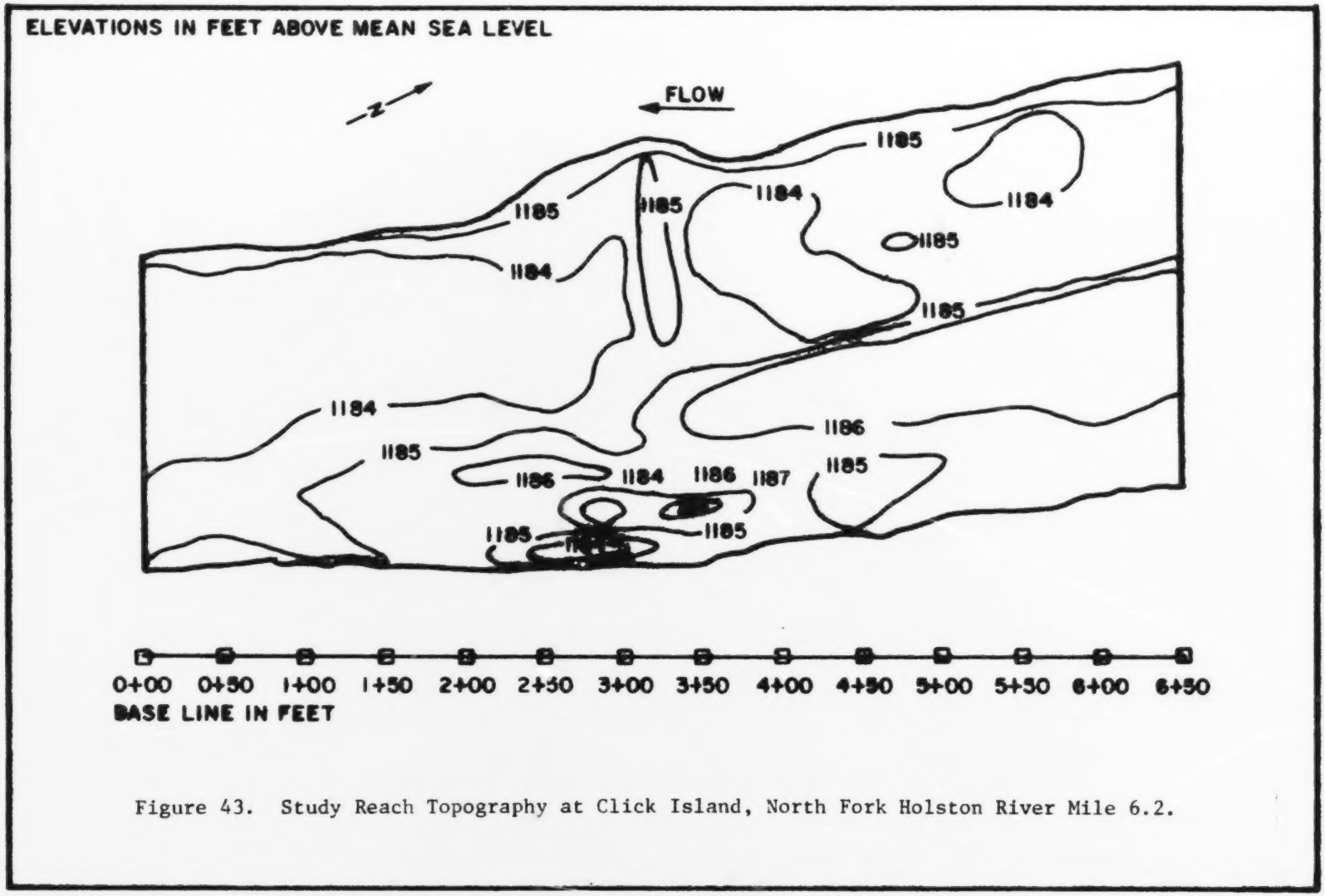

Figure 43. Study Reach Topography at Click Island, North Fork Holston River Mile 6.2.

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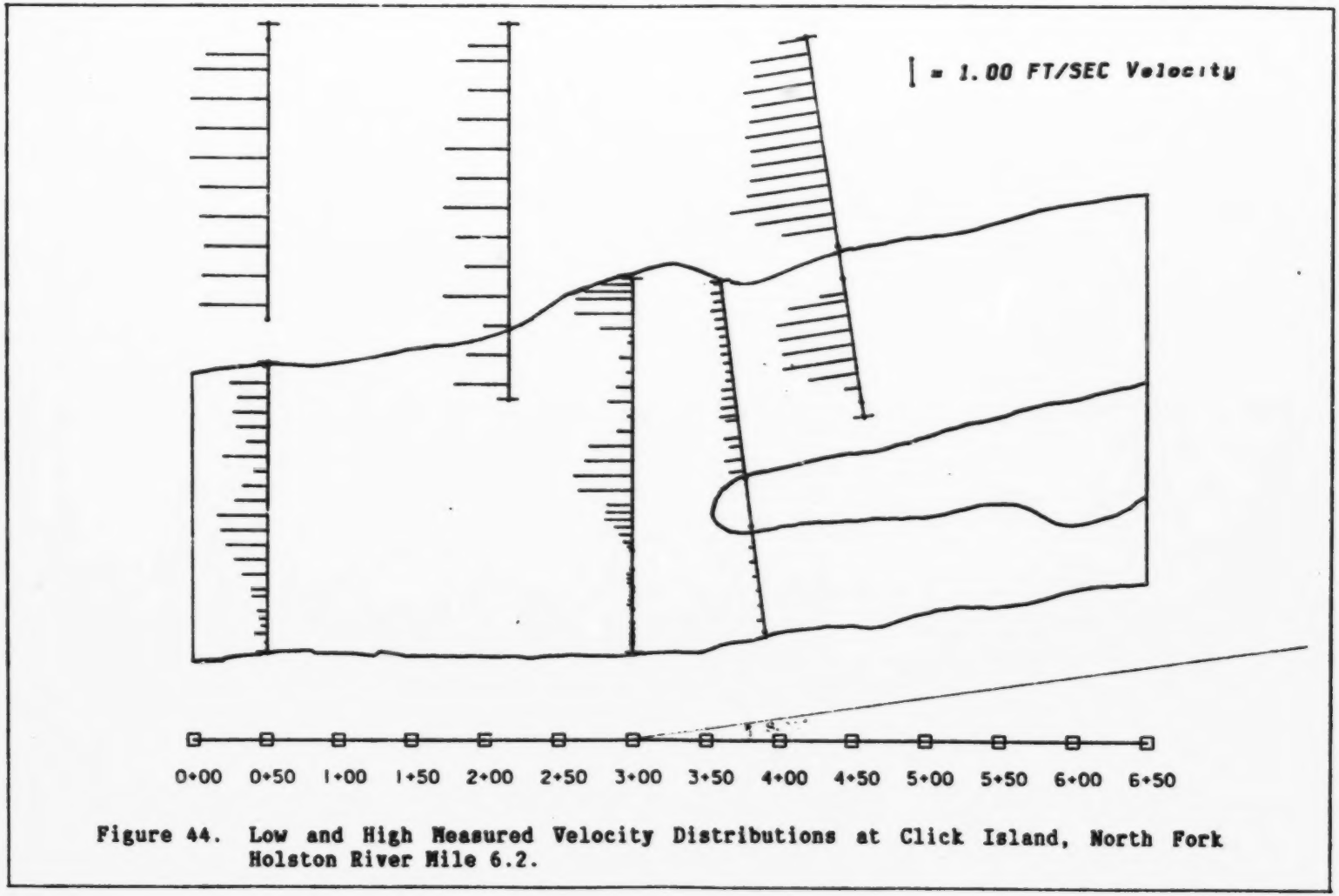
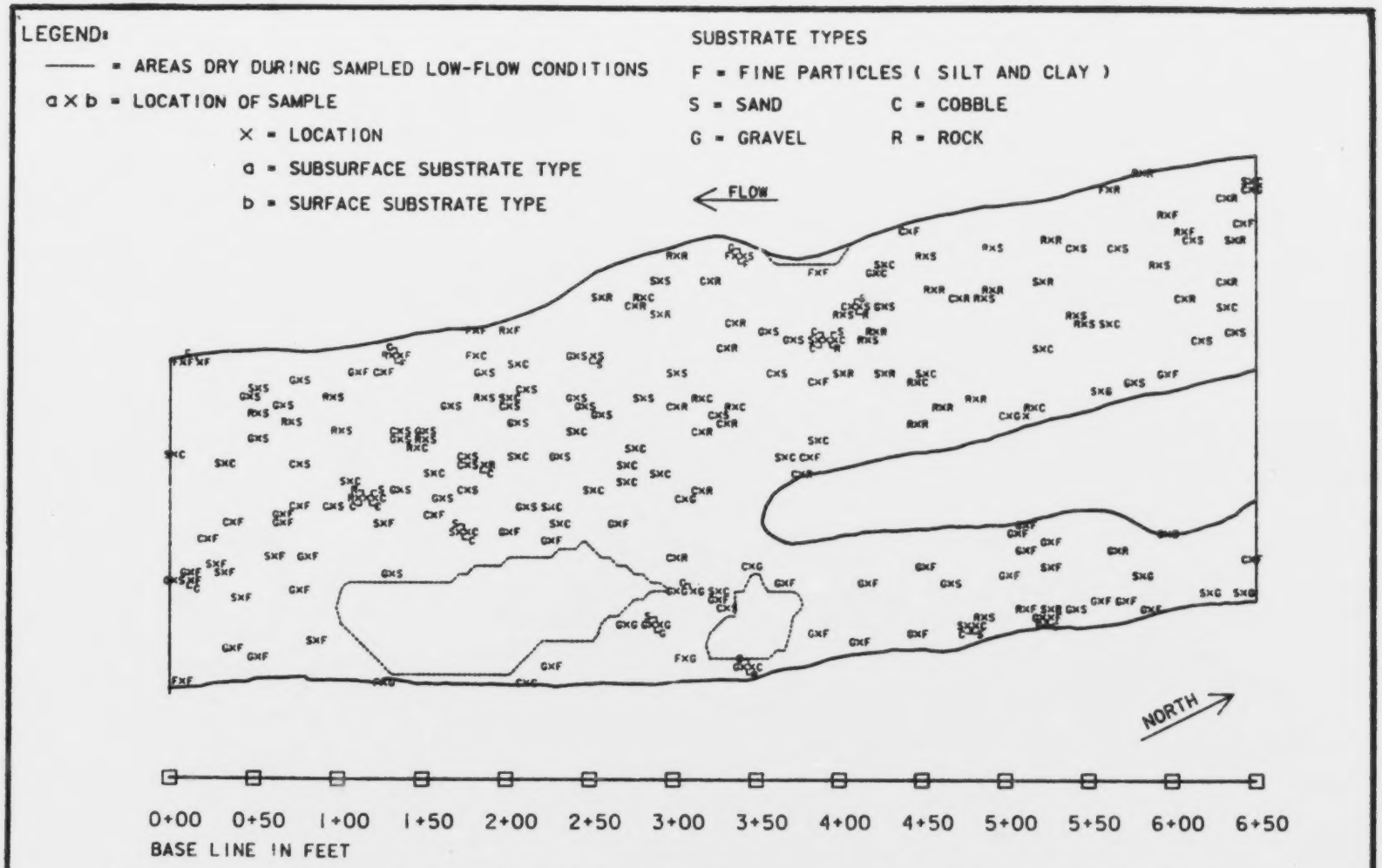


Figure 44. Low and High Measured Velocity Distributions at Click Island, North Fork Holston River Mile 6.2.

BEST COPY AVAILABLE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a × b = LOCATION OF SAMPLE
× = LOCATION
a = SUBSURFACE SUBSTRATE TYPE
b = SURFACE SUBSTRATE TYPE
SUBSTRATE TYPES
F = FINE PARTICLES (SILT AND CLAY)
S = SAND
C = COBBLE
G = GRAVEL
R = ROCK
FLOW
NORTH
0+00 0+50 1+00 1+50 2+00 2+50 3+00 3+50 4+00 4+50 5+00 5+50 6+00 6+50
BASE LINE IN FEET

Figure 45. Surface and Subsurface (3-inch Depth) Substrate Composition at Click Island, North Fork Holston River Mile 6.2.

BEST COPY AVAILABLE

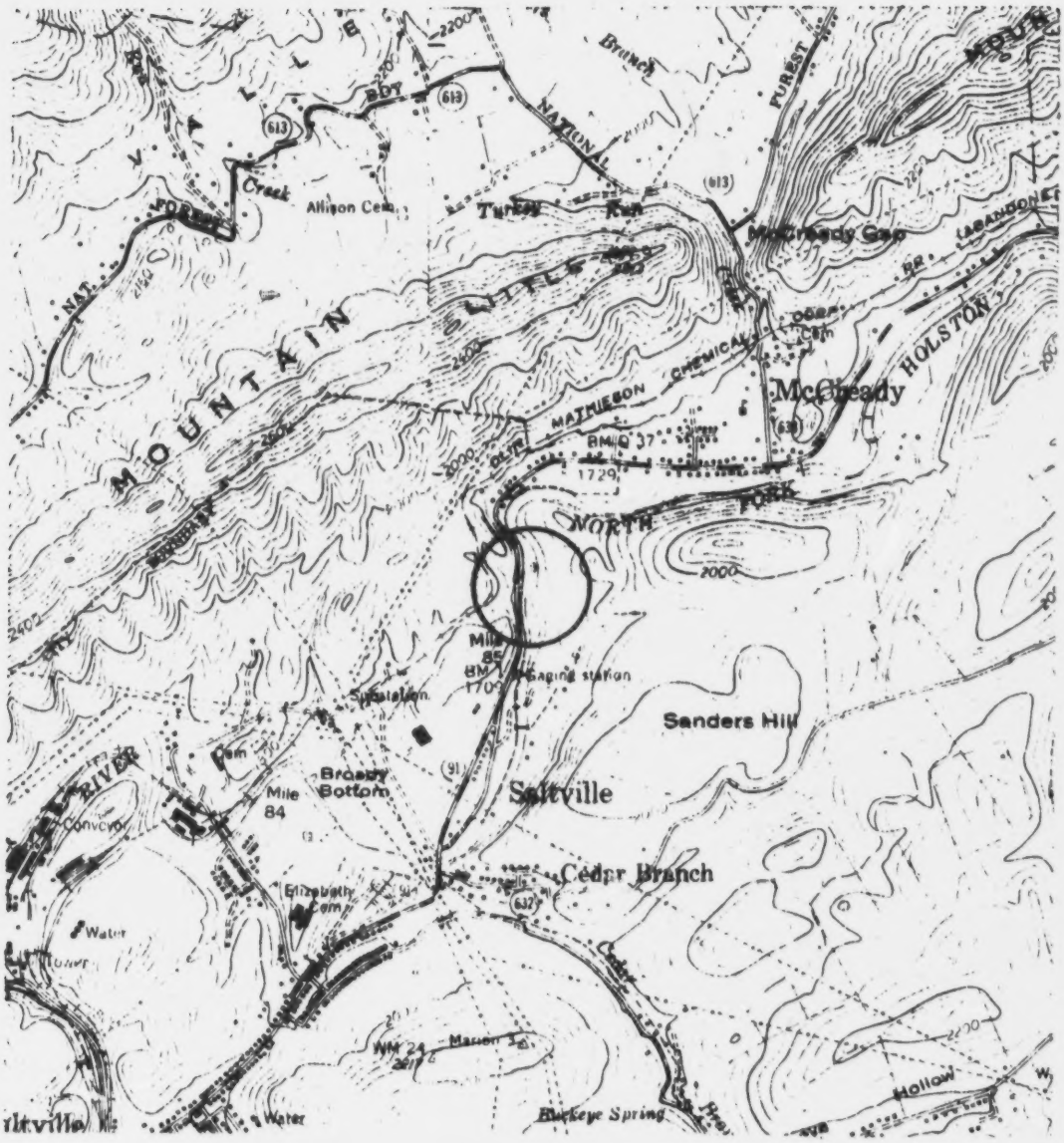

Figure 46. Topography at Saltville, N. Fork Holston River, RM 85.2 (From Quadrangle Maps 218NW, Broadford, Virginia, and 212NE, Saltville, Virginia).

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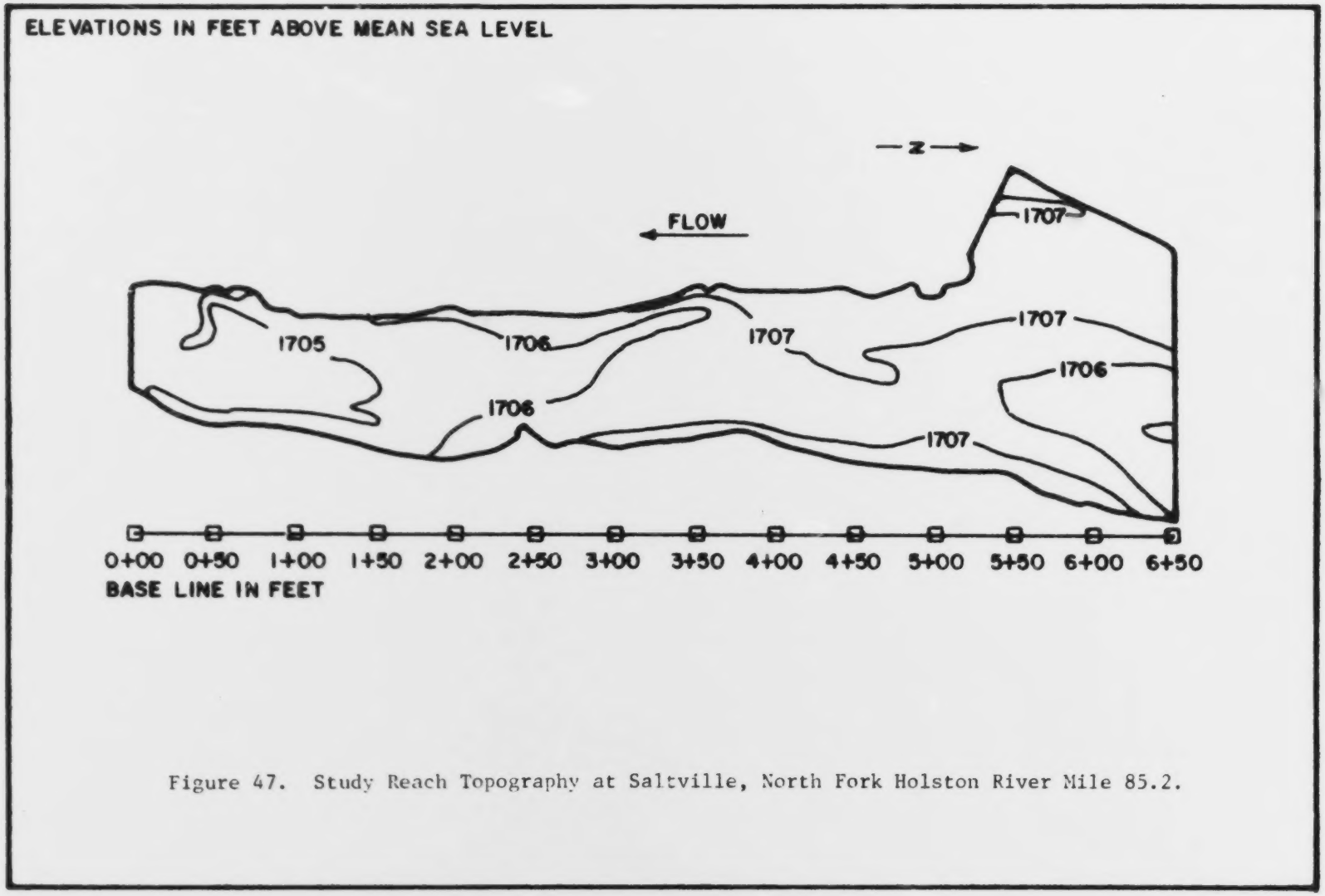

Figure 47. Study Reach Topography at Saltville, North Fork Holston River Mile 85.2.

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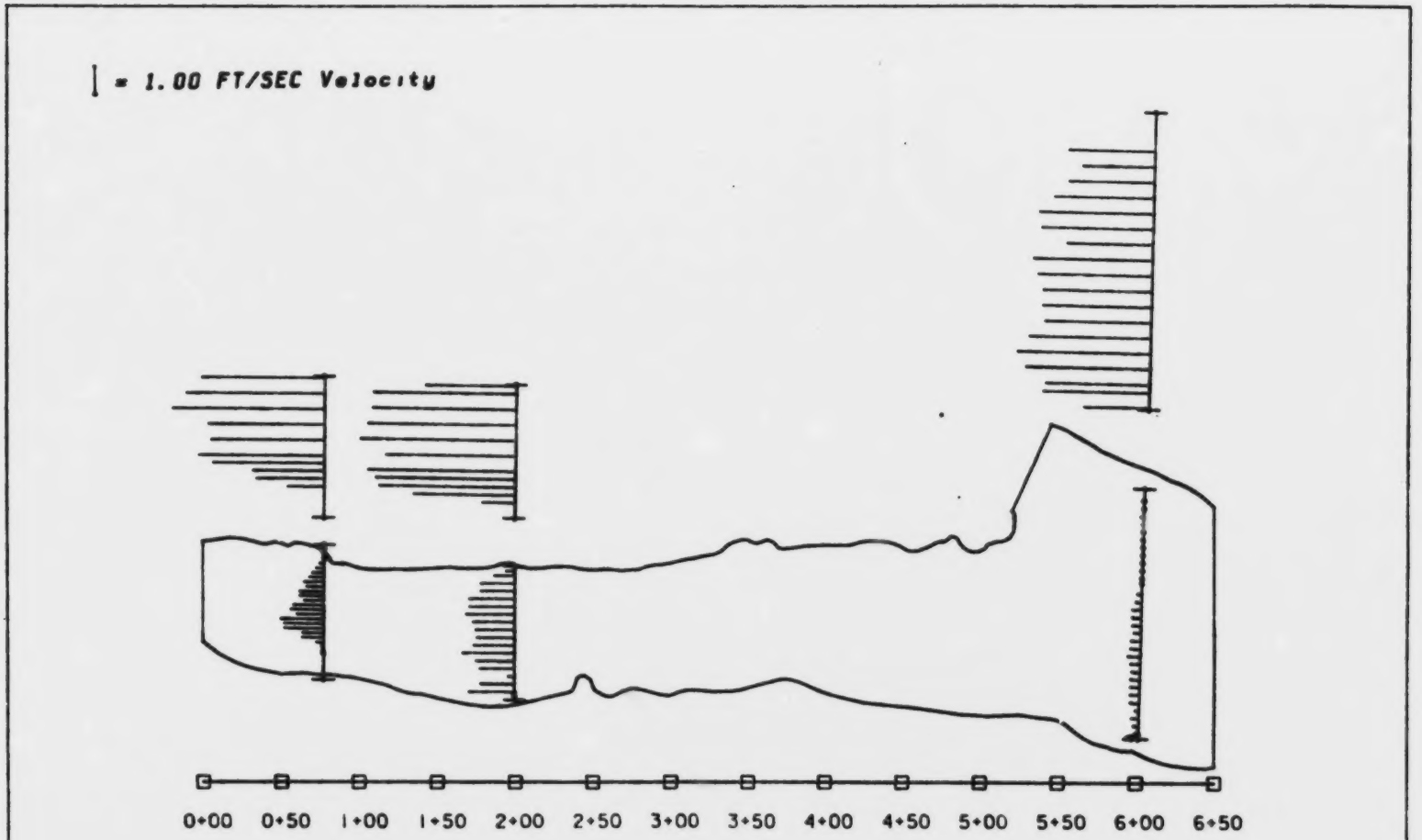

Figure 48. Low and High Measured Velocity Distributions at Saltville, North Fork Holston River Mile 85.2.

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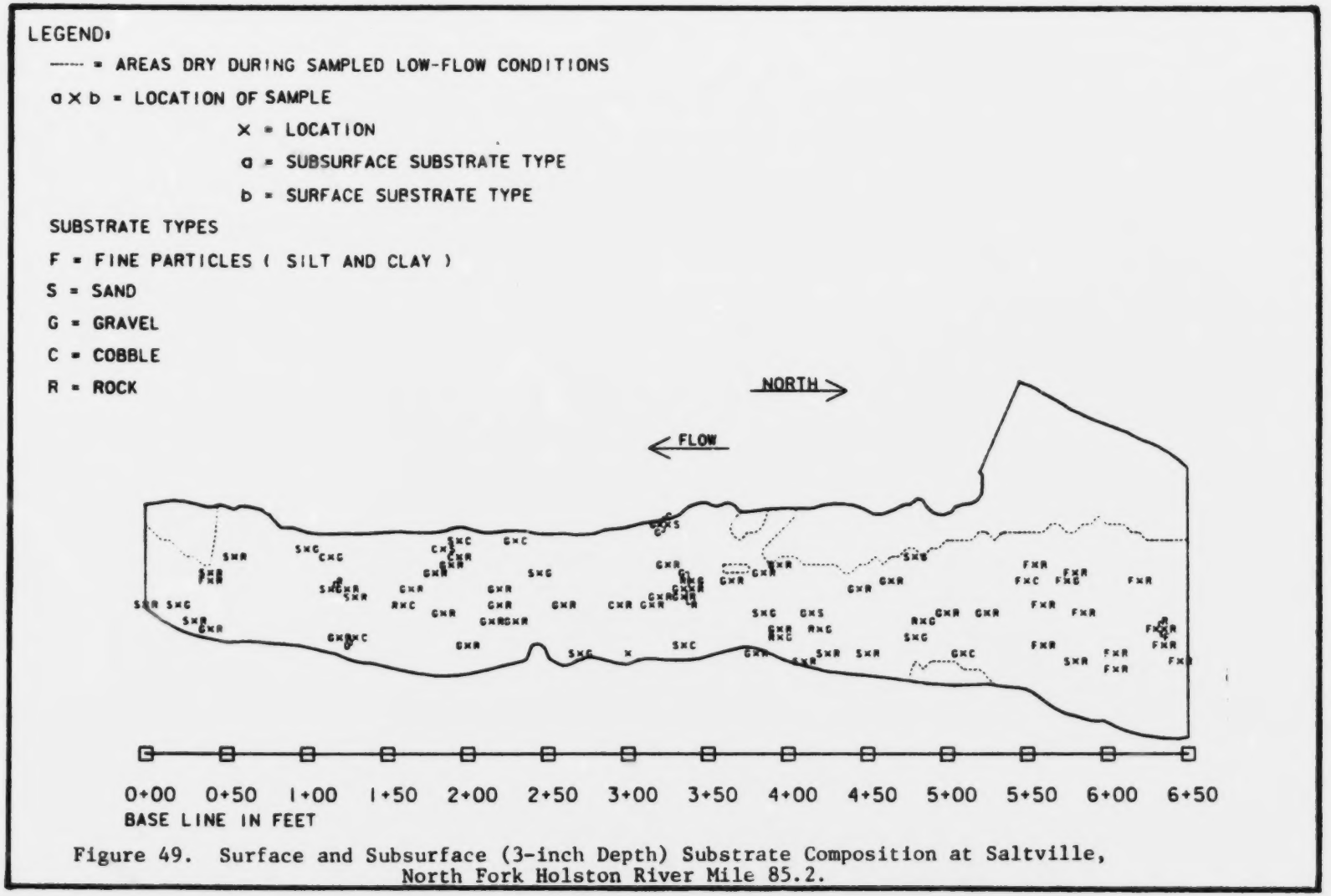
102


LEGEND:
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a X b = LOCATION OF SAMPLE
X = LOCATION
a = SUBSURFACE SUBSTRATE TYPE
b = SURFACE SUBSTRATE TYPE
SUBSTRATE TYPES
F = FINE PARTICLES (SILT AND CLAY)
S = SAND
G = GRAVEL
C = COBBLE
R = ROCK
NORTH
FLOW
0+00 0+50 1+00 1+50 2+00 2+50 3+00 3+50 4+00 4+50 5+00 5+50 6+00 6+50
BASE LINE IN FEET

Figure 49. Surface and Subsurface (3-inch Depth) Substrate Composition at Saltville, North Fork Holston River Mile 85.2.

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103

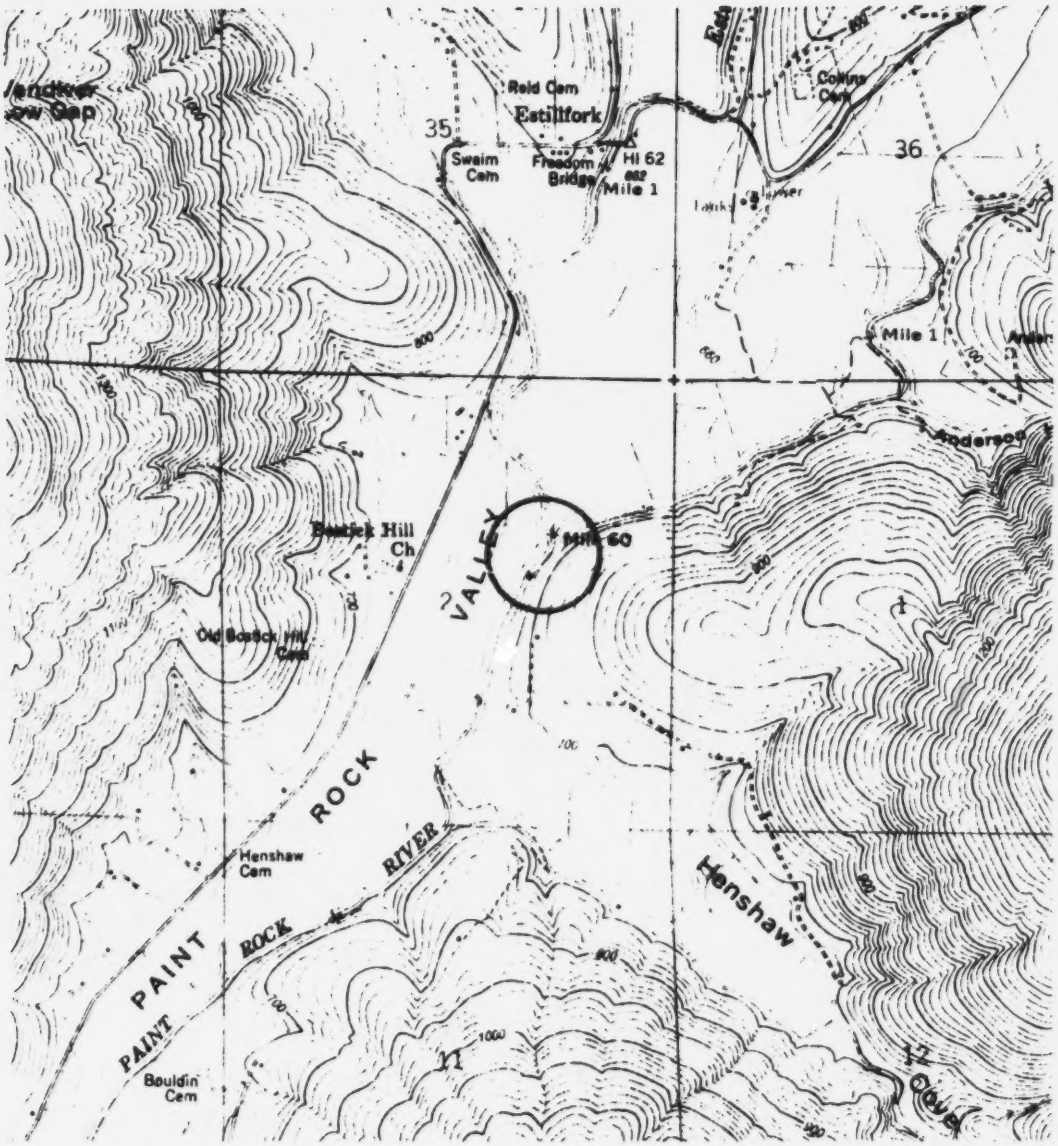

Figure 50. Topography at Estill Fork, Paint Rock River, RM 60.0 (From Quadrangle Map 88NW, Estill Fork, Alabama).

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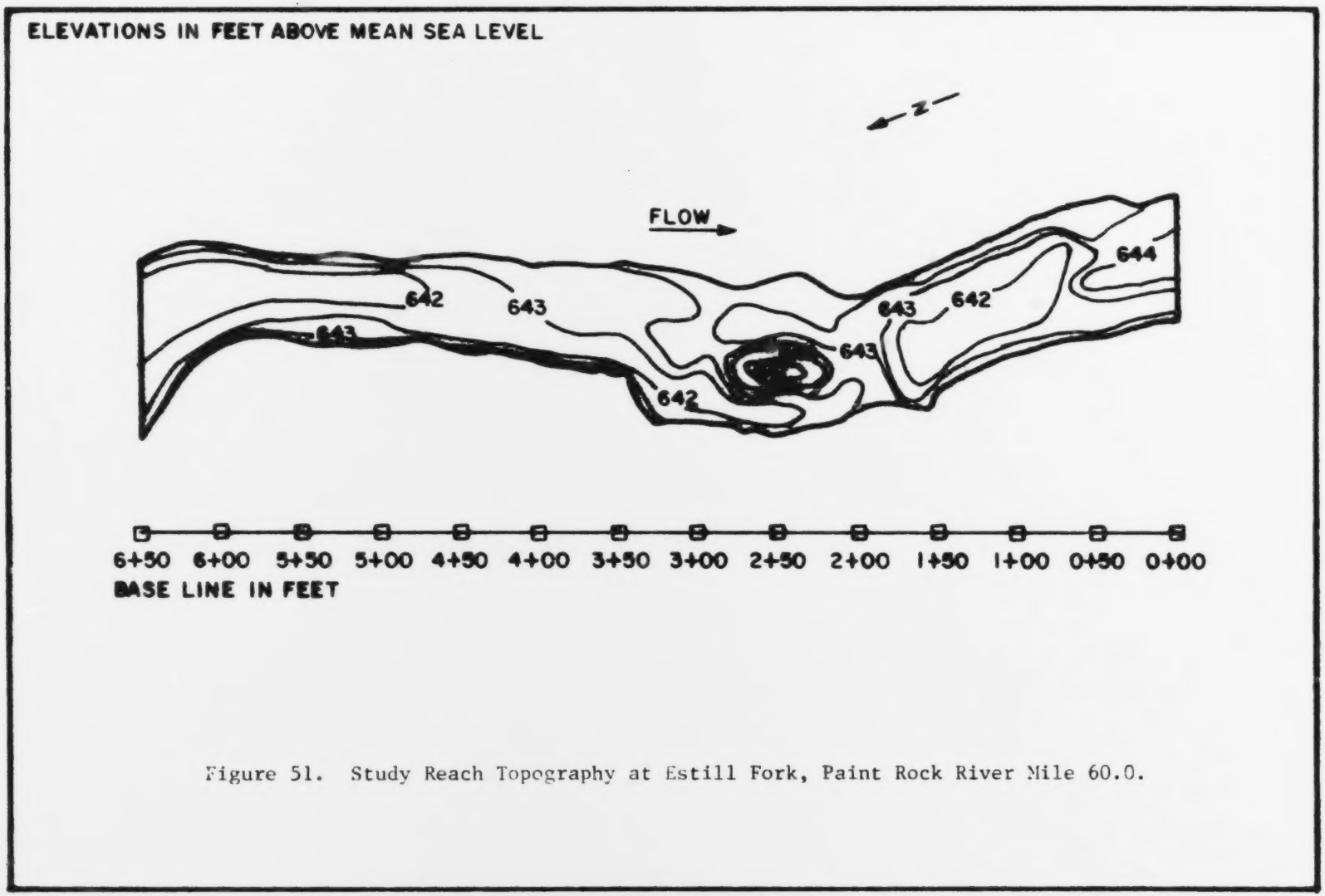

Figure 51. Study Reach Topography at Estill Fork, Paint Rock River Mile 60.0.

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105

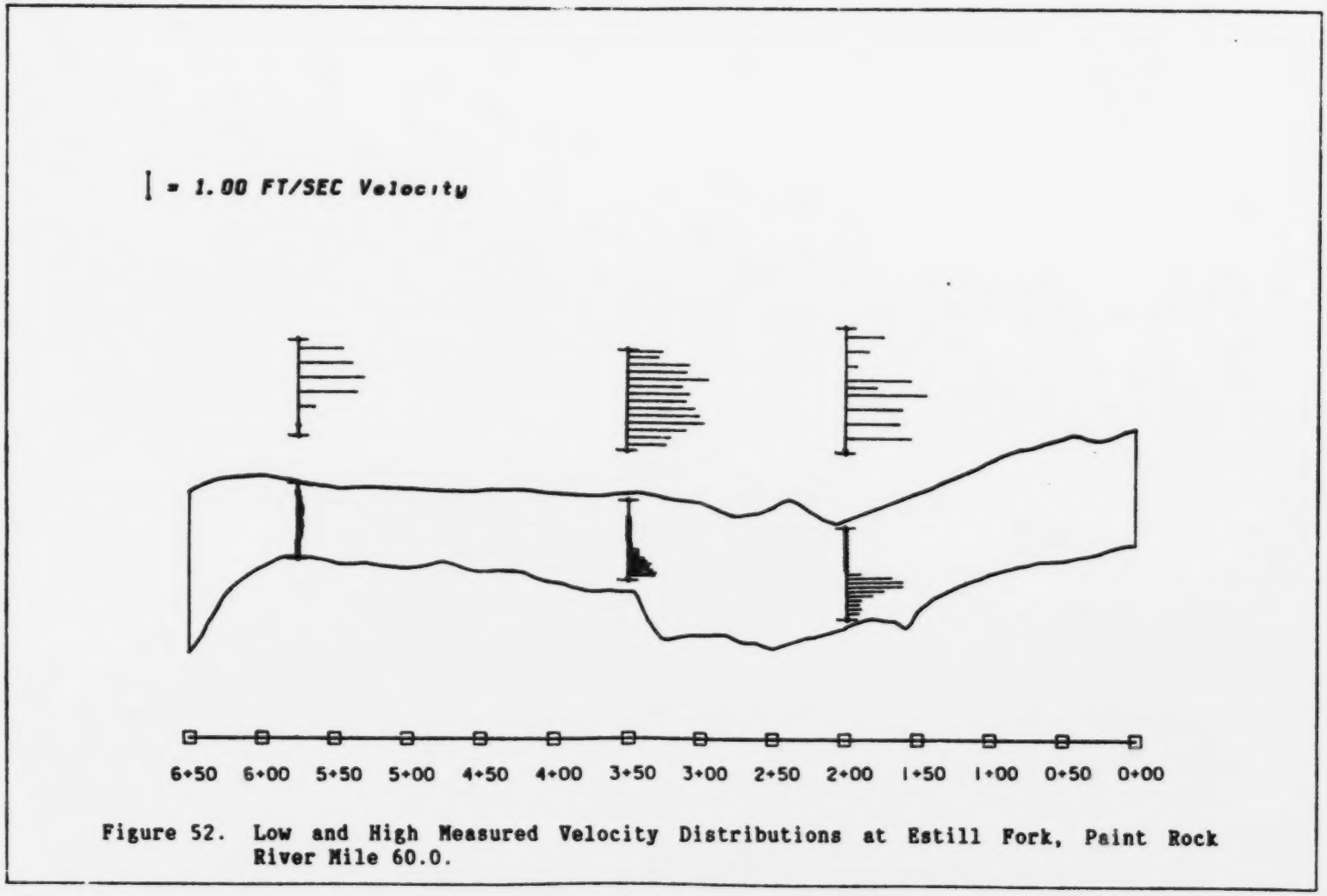


Figure 52. Low and High Measured Velocity Distributions at Estill Fork, Paint Rock River Mile 60.0.

BEST COPY AVAILABLE

LEGEND:

------ = AREAS DRY DURING SAMPLED LOW-FLOW CONDITIONS

a X b = LOCATION OF SAMPLE

X = LOCATION

a = SUBSURFACE SUBSTRATE TYPE

b = SURFACE SUBSTRATE TYPE

SUBSTRATE TYPES

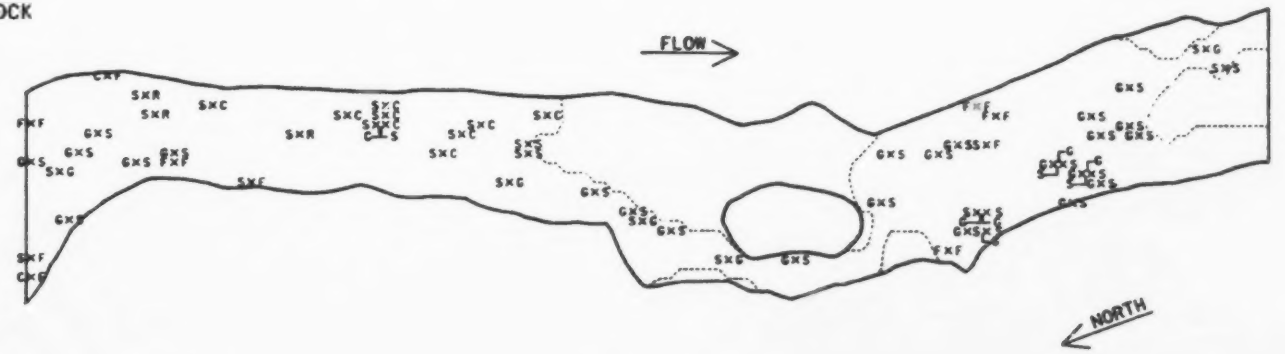
F = FINE PARTICLES (SILT AND CLAY)

S = SAND

G = GRAVEL

C = COBBLE

R = ROCK



6+50 6+00 5+50 5+00 4+50 4+00 3+50 3+00 2+50 2+00 1+50 1+00 0+50 0+00

BASE LINE IN FEET

Figure 53. Surface and Subsurface (3-inch Depth) Substrate Composition at Estill Fork, Paint Rock River Mile 60.0.

BEST COPY AVAILABLE

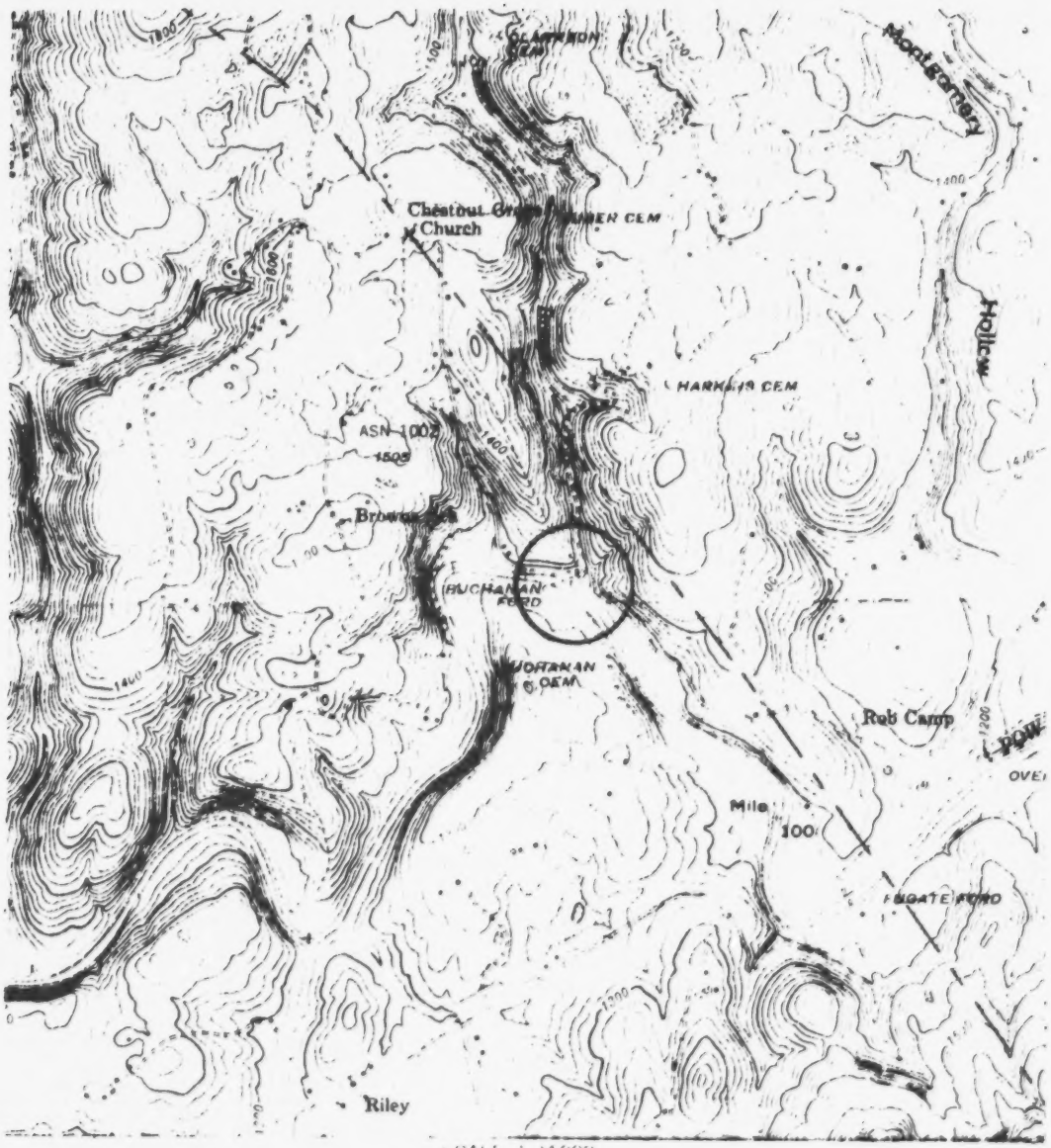


Figure 54. Topography at Buchanan Ford, Powell River, RM 99.2 (From Quadrangle Map 161SW, Coleman Gap, Tennessee-Virginia).

BEST COPY AVAILABLE

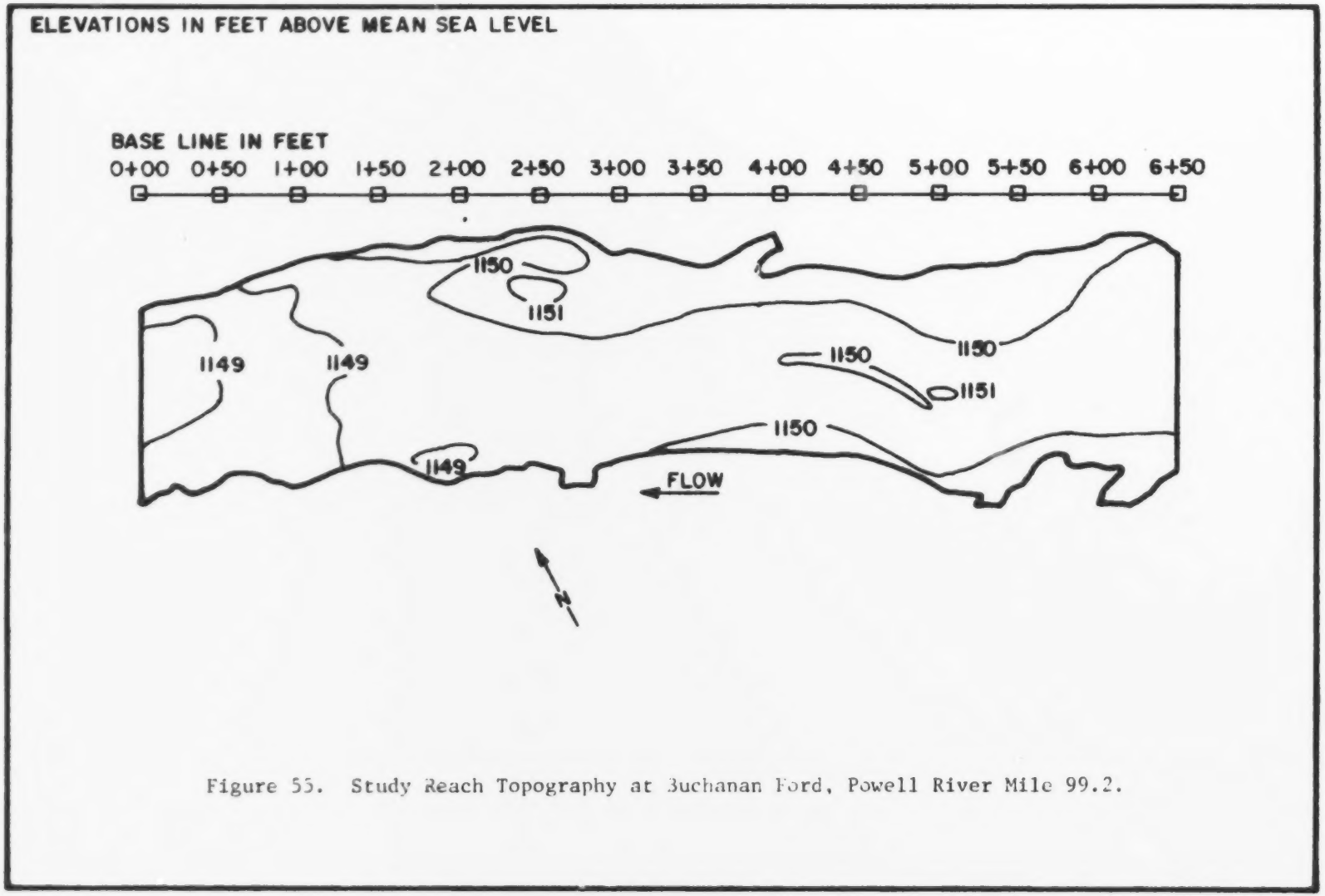


Figure 55. Study Reach Topography at Buchanan Ford, Powell River Mile 99.2.

BEST COPY AVAILABLE

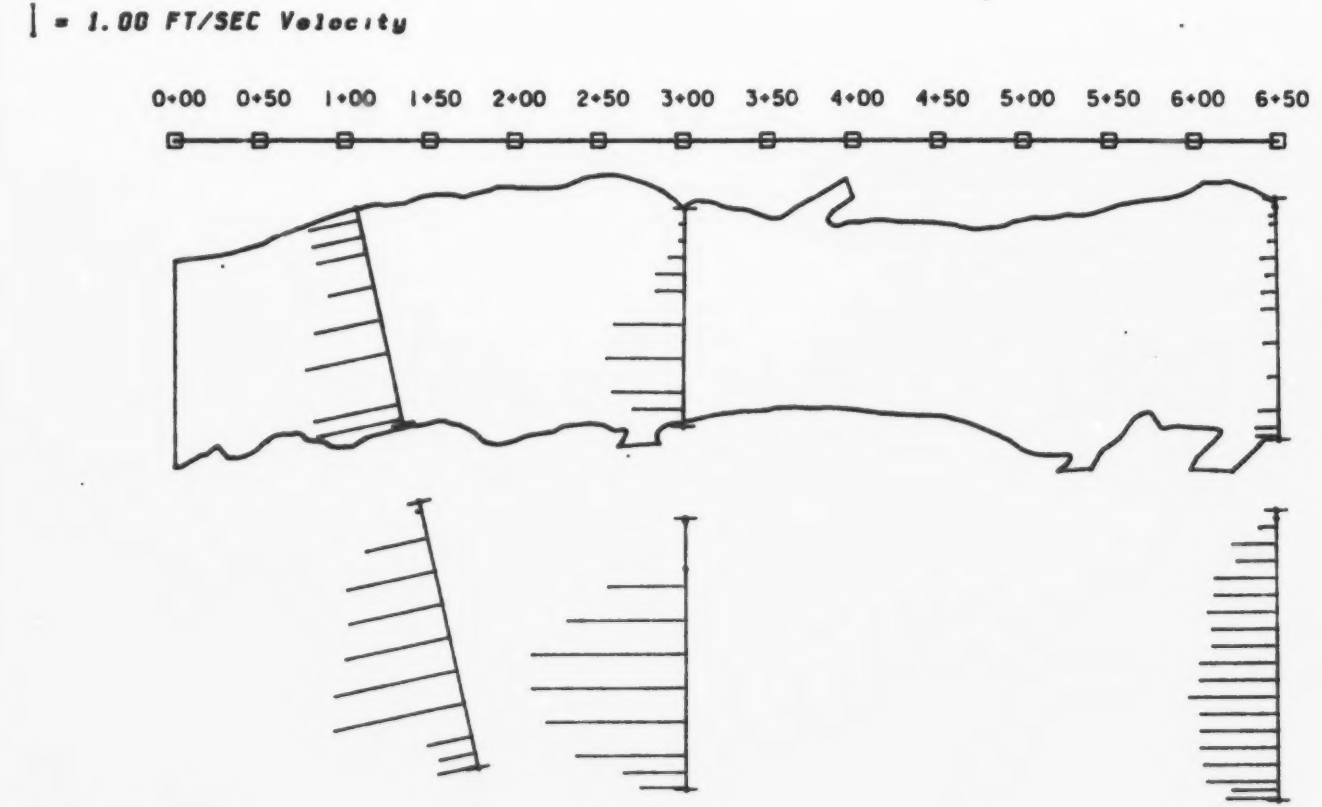
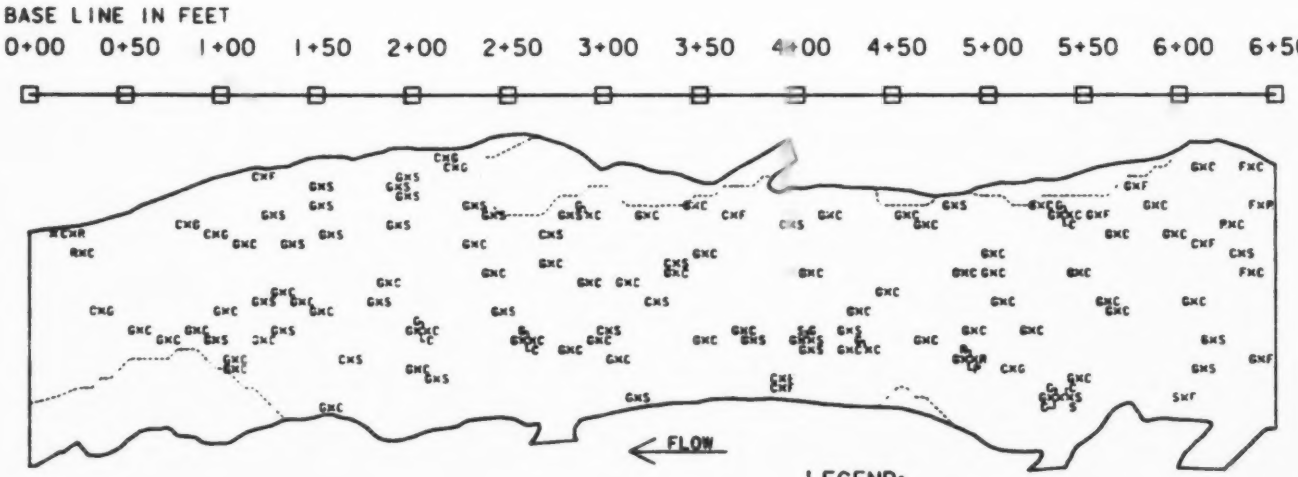


Figure 56. Low and High Measured Velocity Distributions at Buchanan Ford, Powell River Mile 99.2.

BEST COPY AVAILABLE



LEGEND:

—— = AREAS DRY DURING SAMPLED LOW-FLOW CONDITIONS

a X b = LOCATION OF SAMPLE

X = LOCATION

a = SUBSURFACE SUBSTRATE TYPE

b = SURFACE SUBSTRATE TYPE

SUBSTRATE TYPES

F = FINE PARTICLES (SILT AND CLAY)

S = SAND C = COBBLE

G = GRAVEL R = ROCK

Figure 57. Surface and Subsurface (3-inch Depth) Substrate Composition at Buchanan Ford, Powell River Mile 99.2.

BEST COPY AVAILABLE

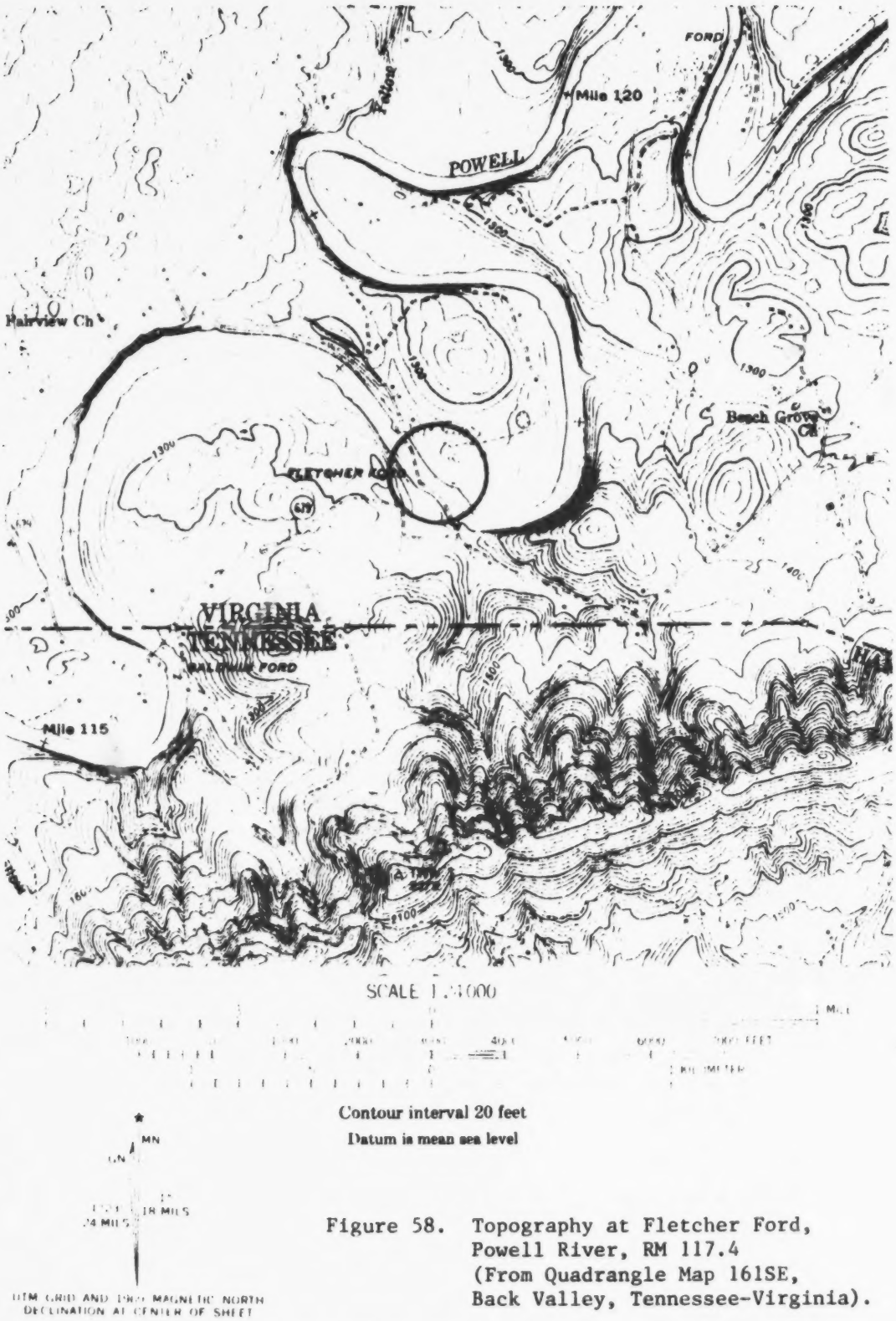


Figure 58. Topography at Fletcher Ford, Powell River, RM 117.4 (From Quadrangle Map 161SE, Back Valley, Tennessee-Virginia).

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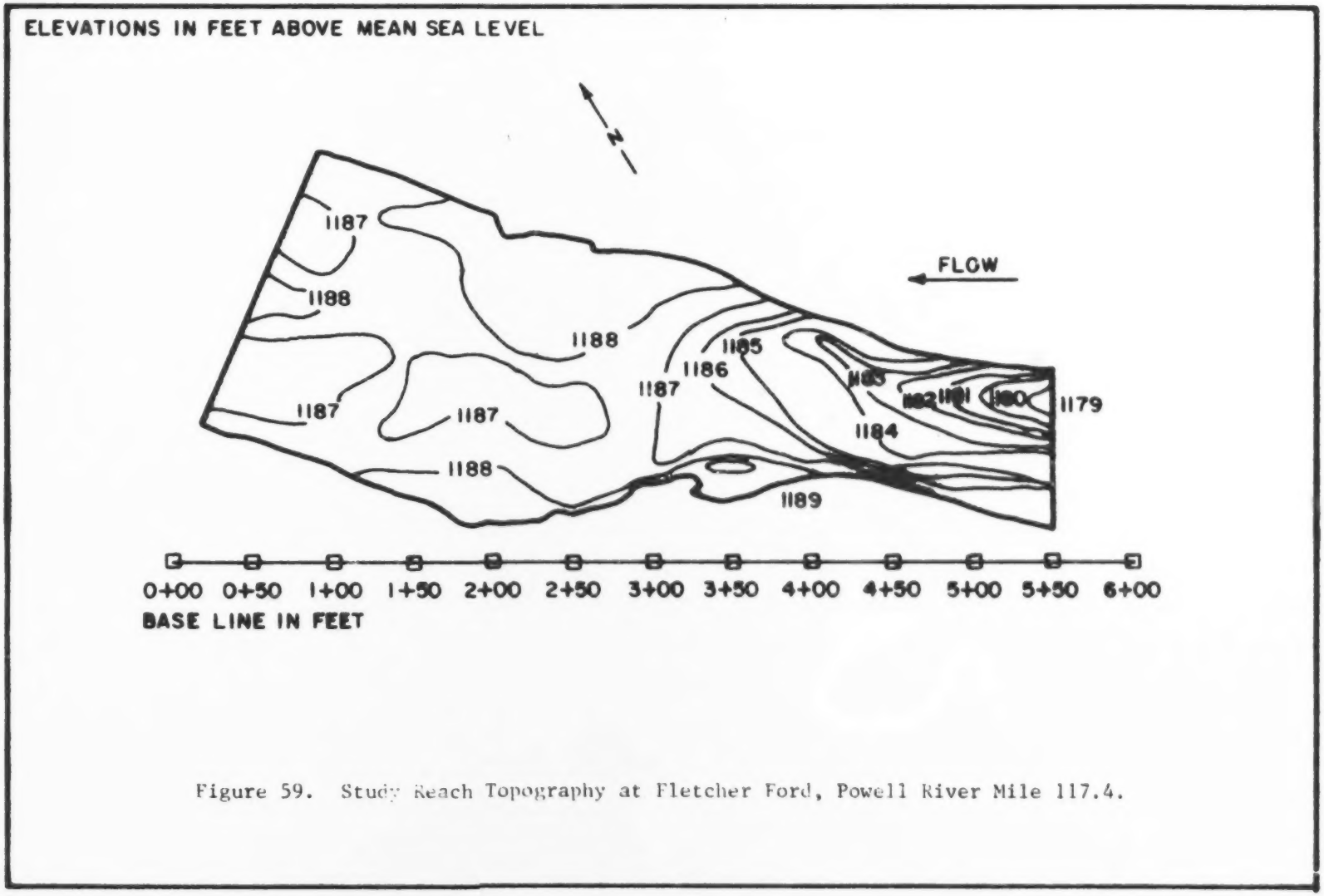

Figure 59. Study Reach Topography at Fletcher Ford, Powell River Mile 117.4.

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113

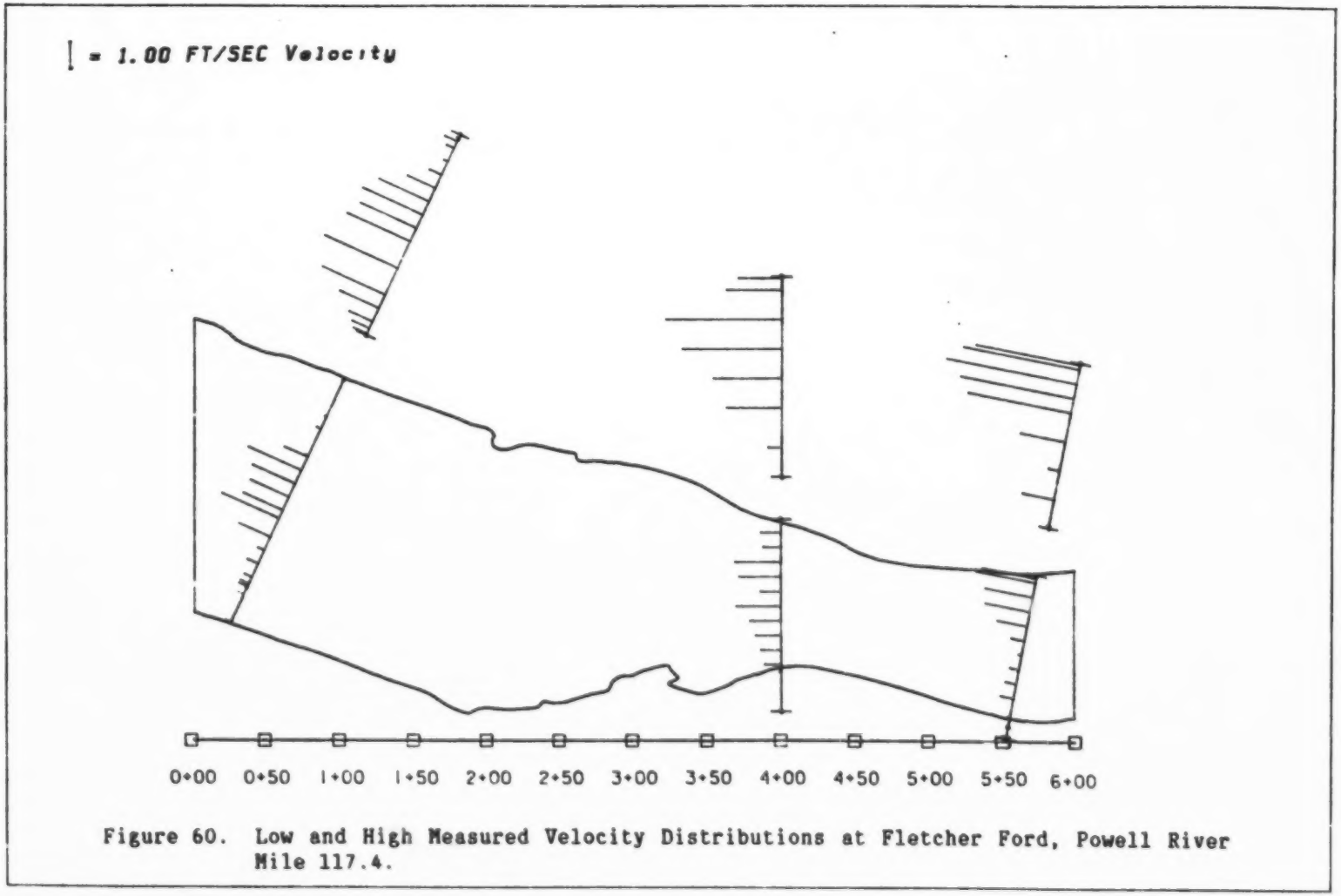
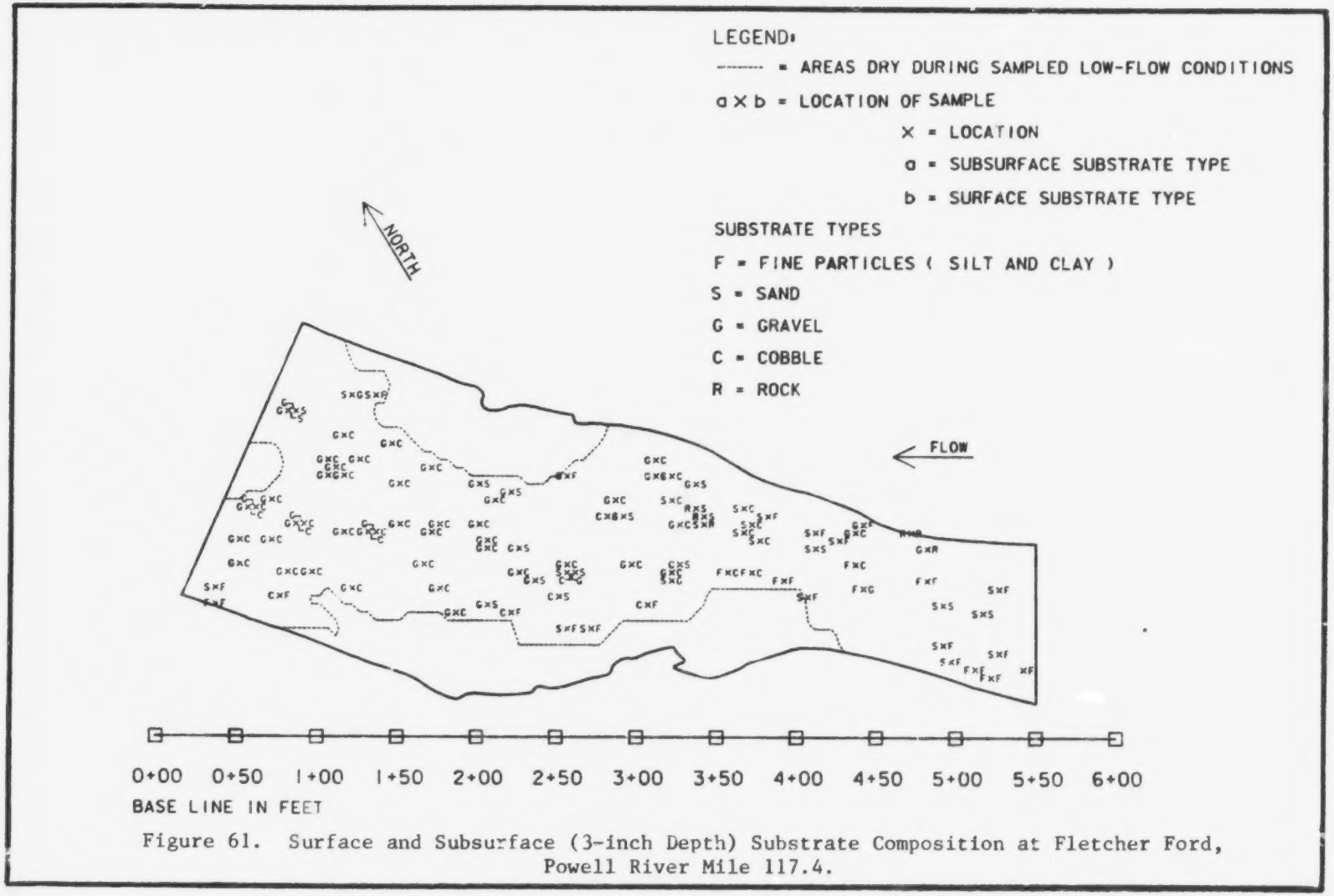


Figure 60. Low and High Measured Velocity Distributions at Fletcher Ford, Powell River Mile 117.4.

BEST COPY AVAILABLE


LEGEND:
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a X b = LOCATION OF SAMPLE
X = LOCATION
a = SUBSURFACE SUBSTRATE TYPE
b = SURFACE SUBSTRATE TYPE
SUBSTRATE TYPES
F = FINE PARTICLES (SILT AND CLAY)
S = SAND
G = GRAVEL
C = COBBLE
R = ROCK
NORTH
FLOW
0+00 0+50 1+00 1+50 2+00 2+50 3+00 3+50 4+00 4+50 5+00 5+50 6+00
BASE LINE IN FEET

Figure 61. Surface and Subsurface (3-inch Depth) Substrate Composition at Fletcher Ford, Powell River Mile 117.4.

BEST COPY AVAILABLE

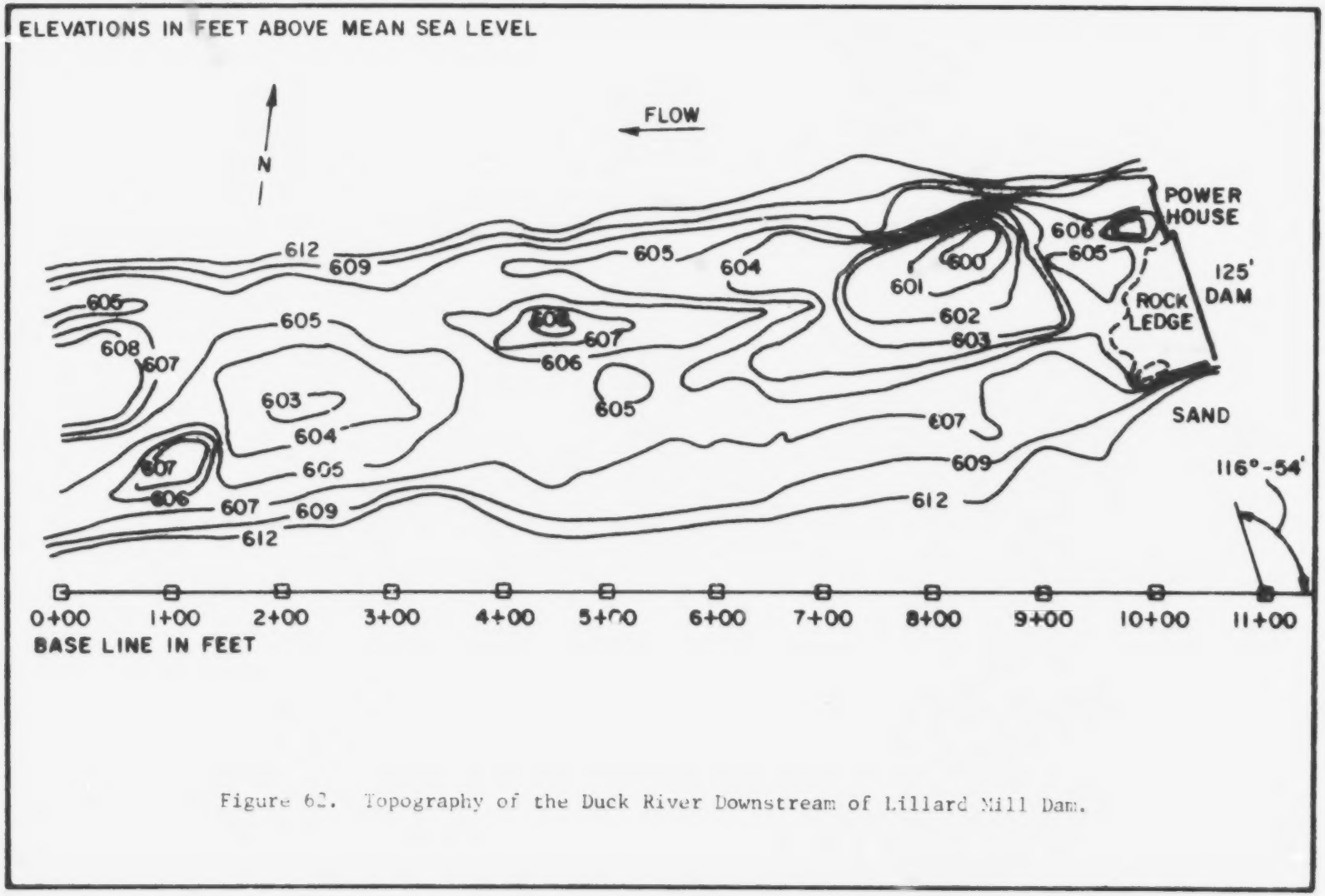

Figure 62. Topography of the Duck River Downstream of Lillard Mill Dam.

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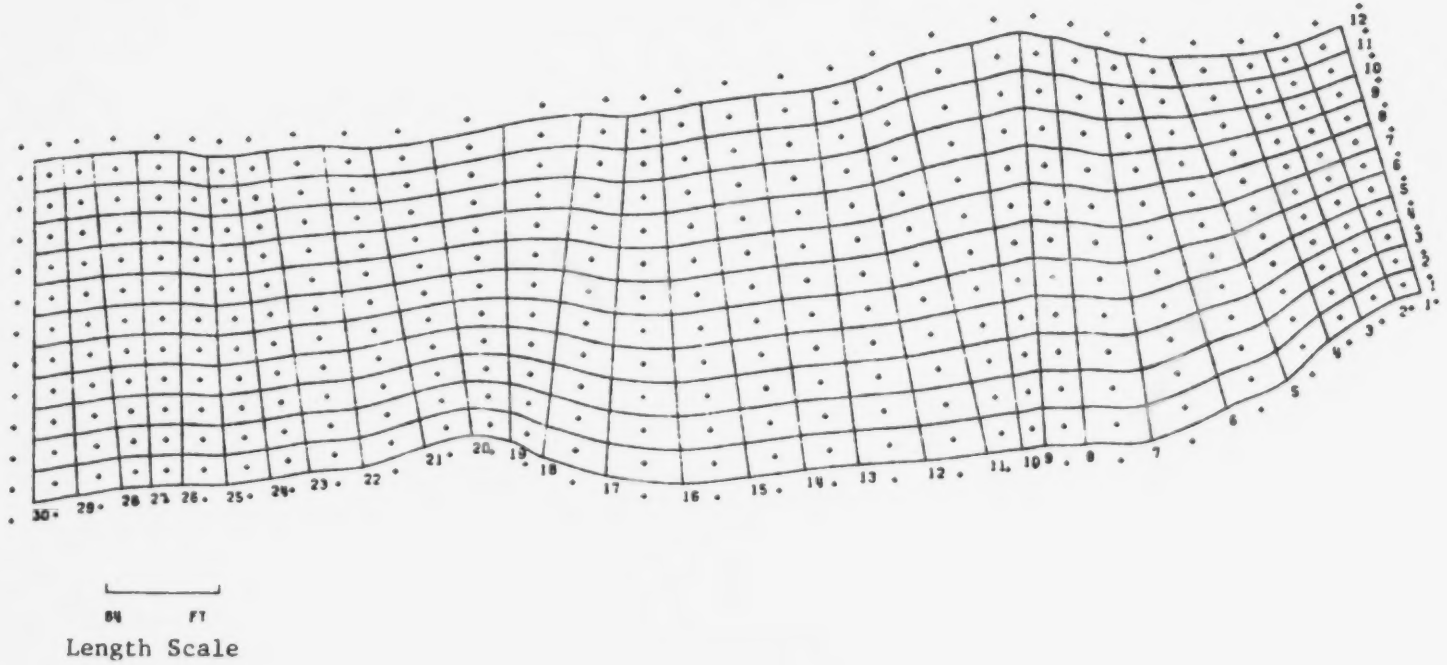

Figure 63. Computer-Generated Grid for Two-Dimensional Modeling of Flow Downstream of Lillard Mill Dam.

BEST COPY AVAILABLE

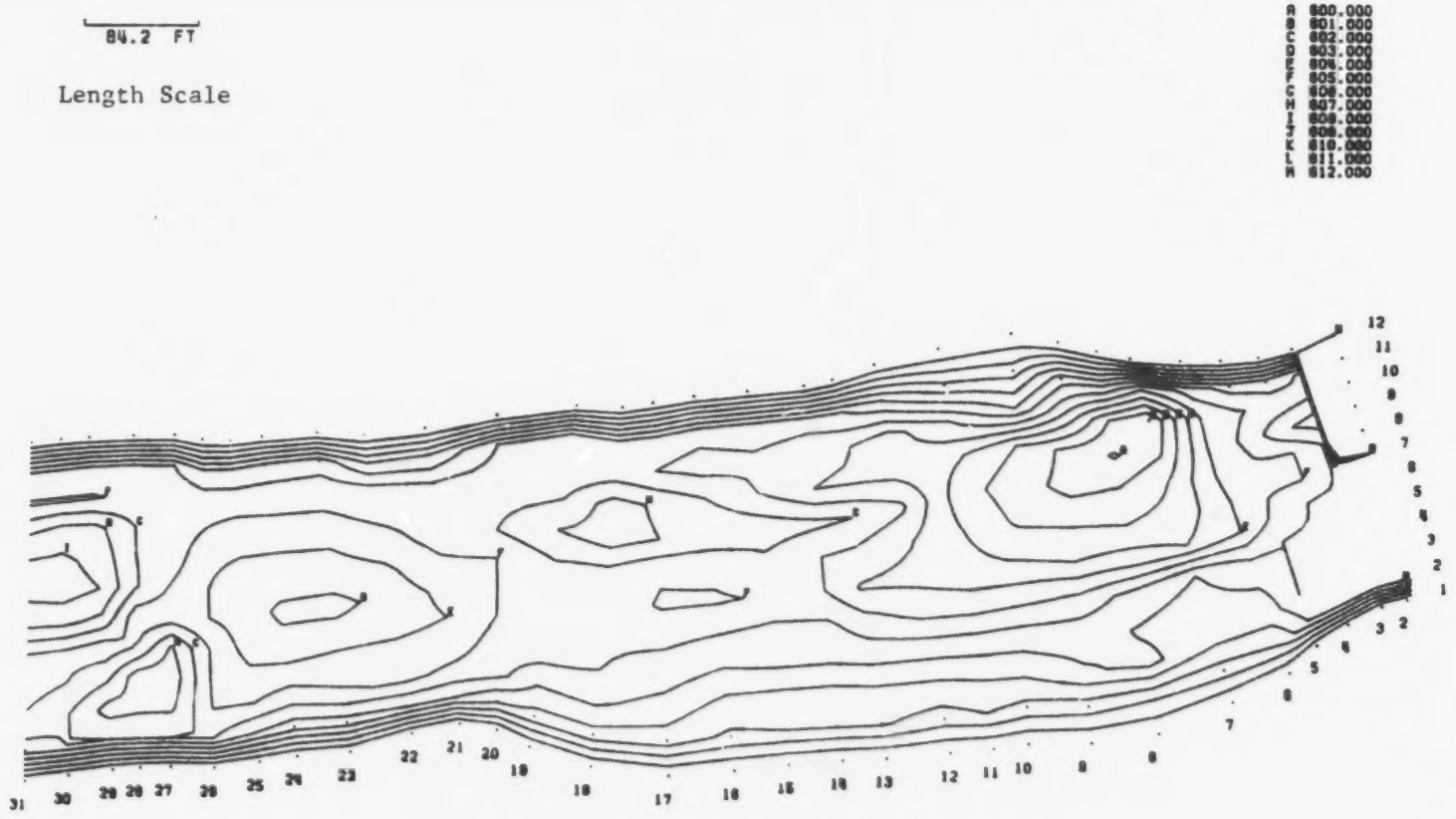

Figure 64. Computer-Generated Topography of the Duck River Downstream of the Lillard Mill Dam.

BEST COPY AVAILABLE

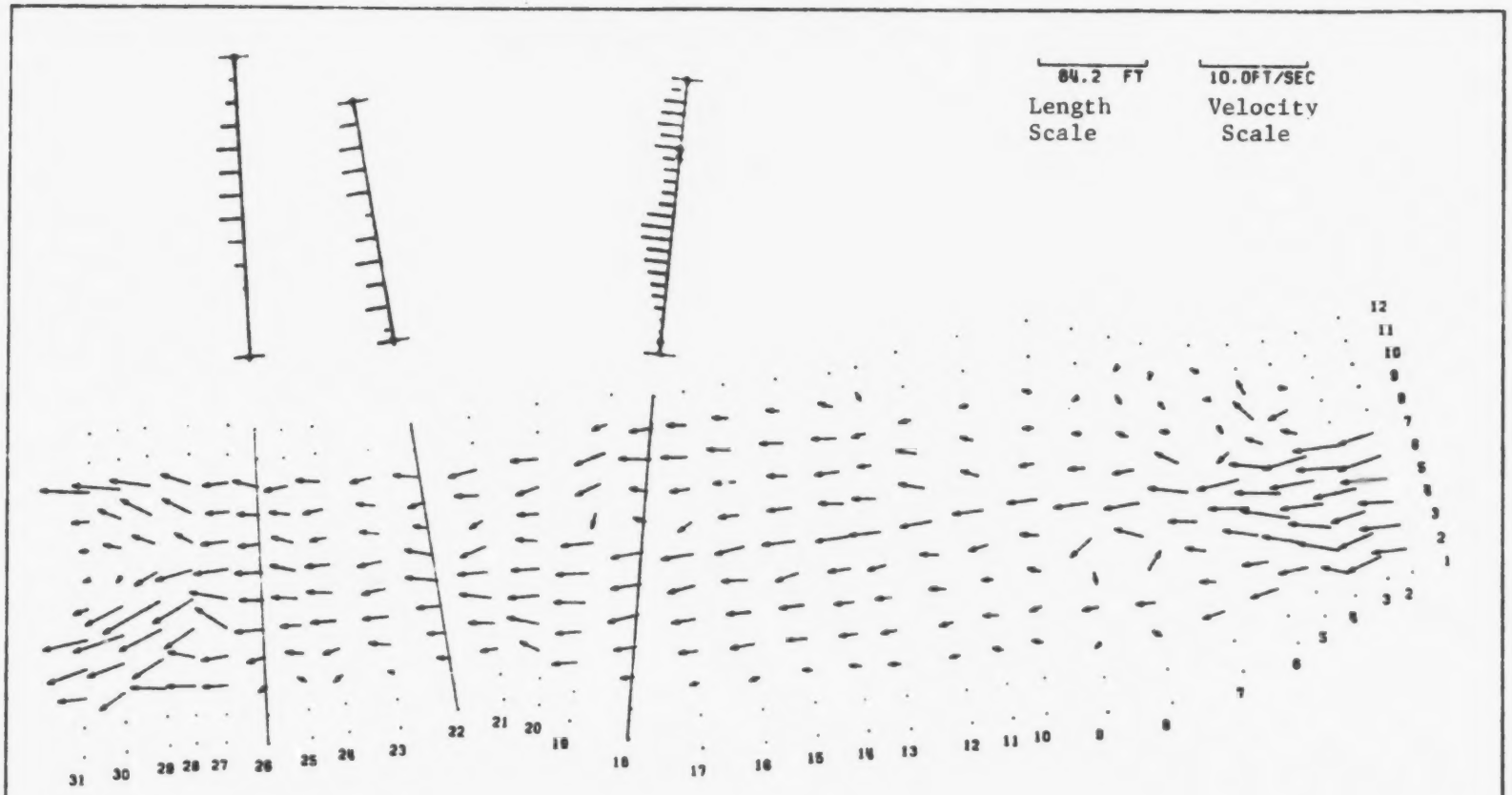

Figure 65. Comparison of Modelled Results With Velocity Measurements Downstream of the Lillard Mill Dam.

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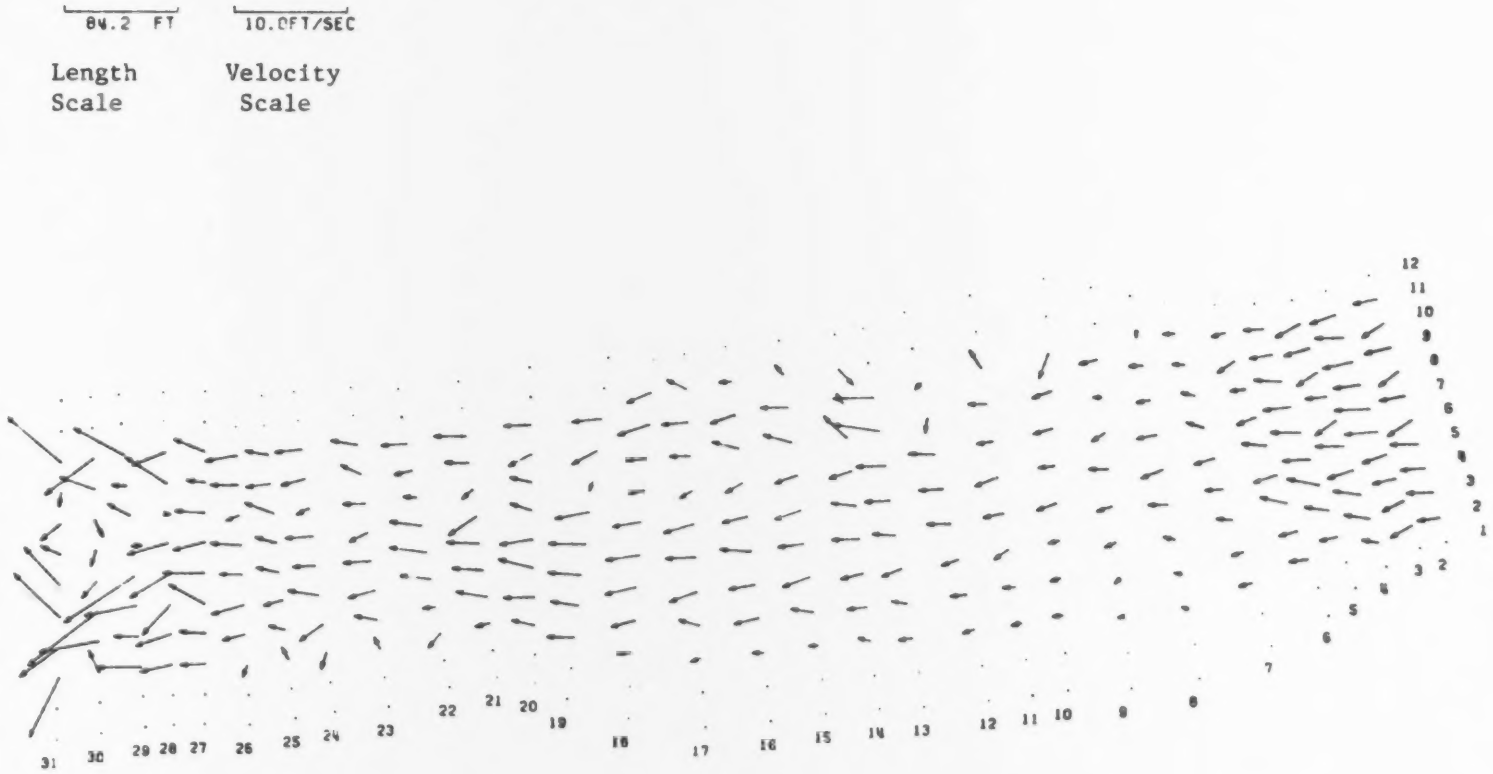

Figure 66. Simulated Velocities in the Duck River Without the Lillard Mill Dam.

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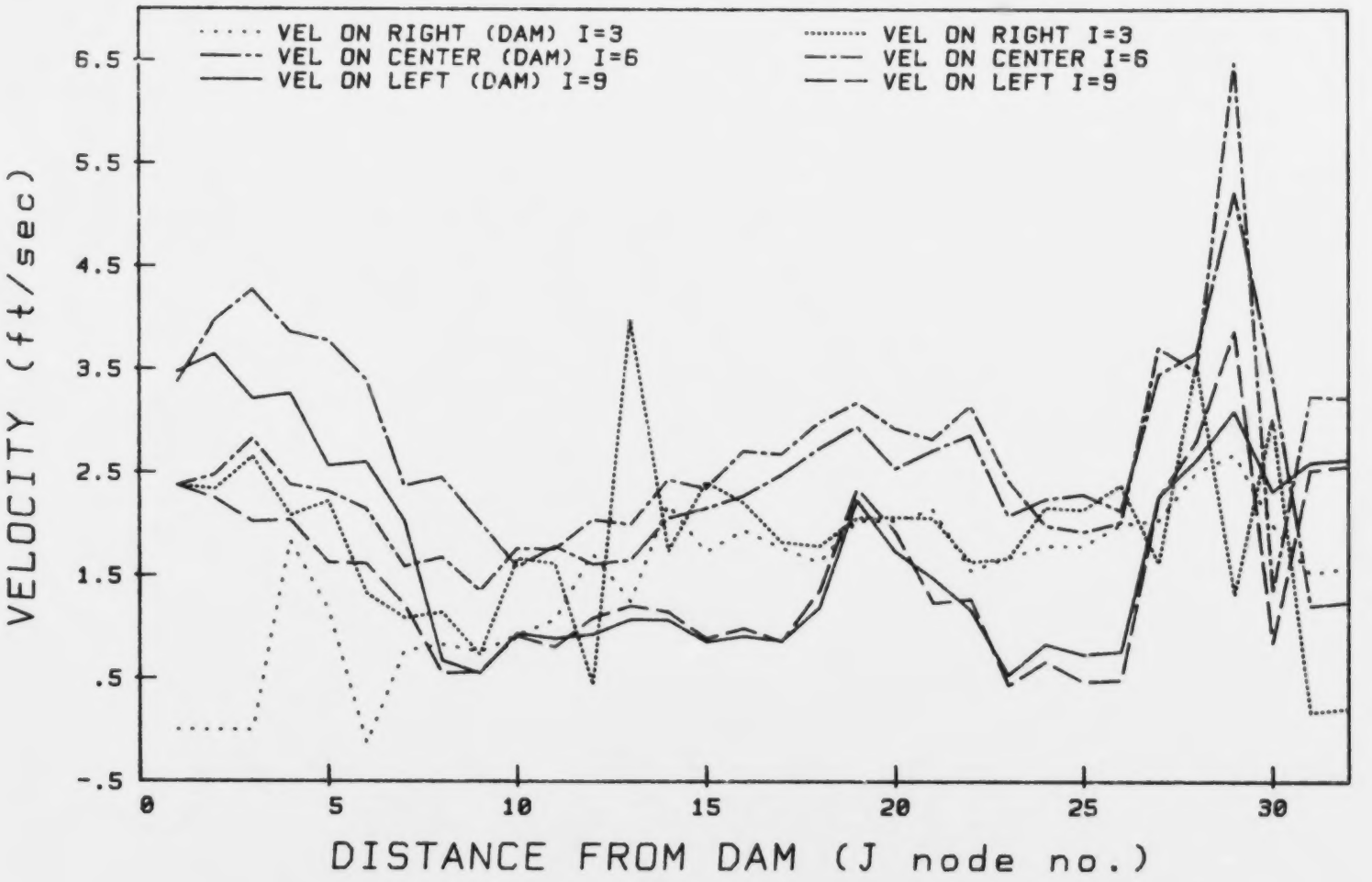

Figure 67. Comparison of Single Point Simulated Velocities With and Without the Lillard Mill Dam.

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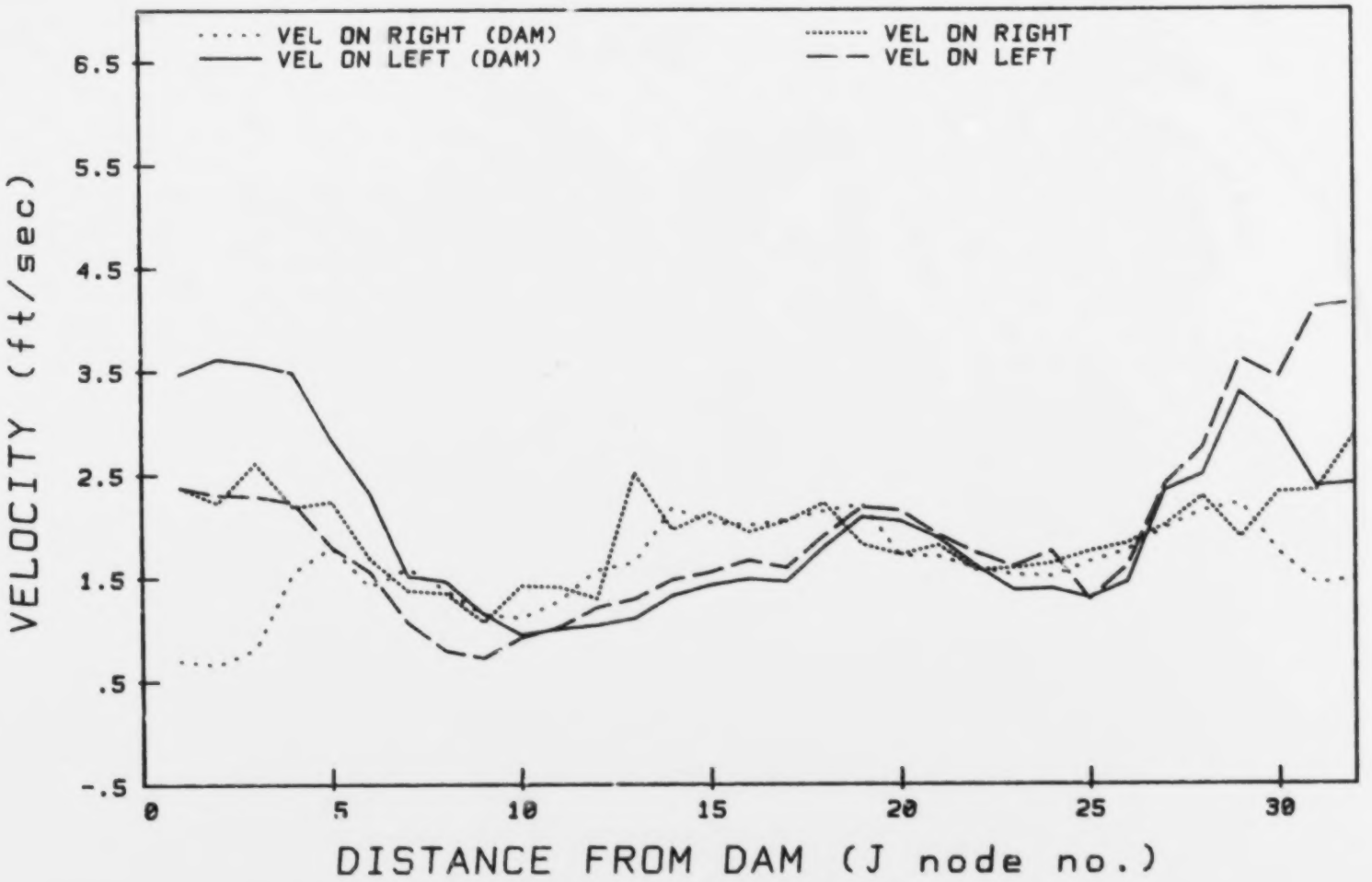

Figure 68. Comparison of Average Simulated Velocities With and Without the Lillard Mill Dam.

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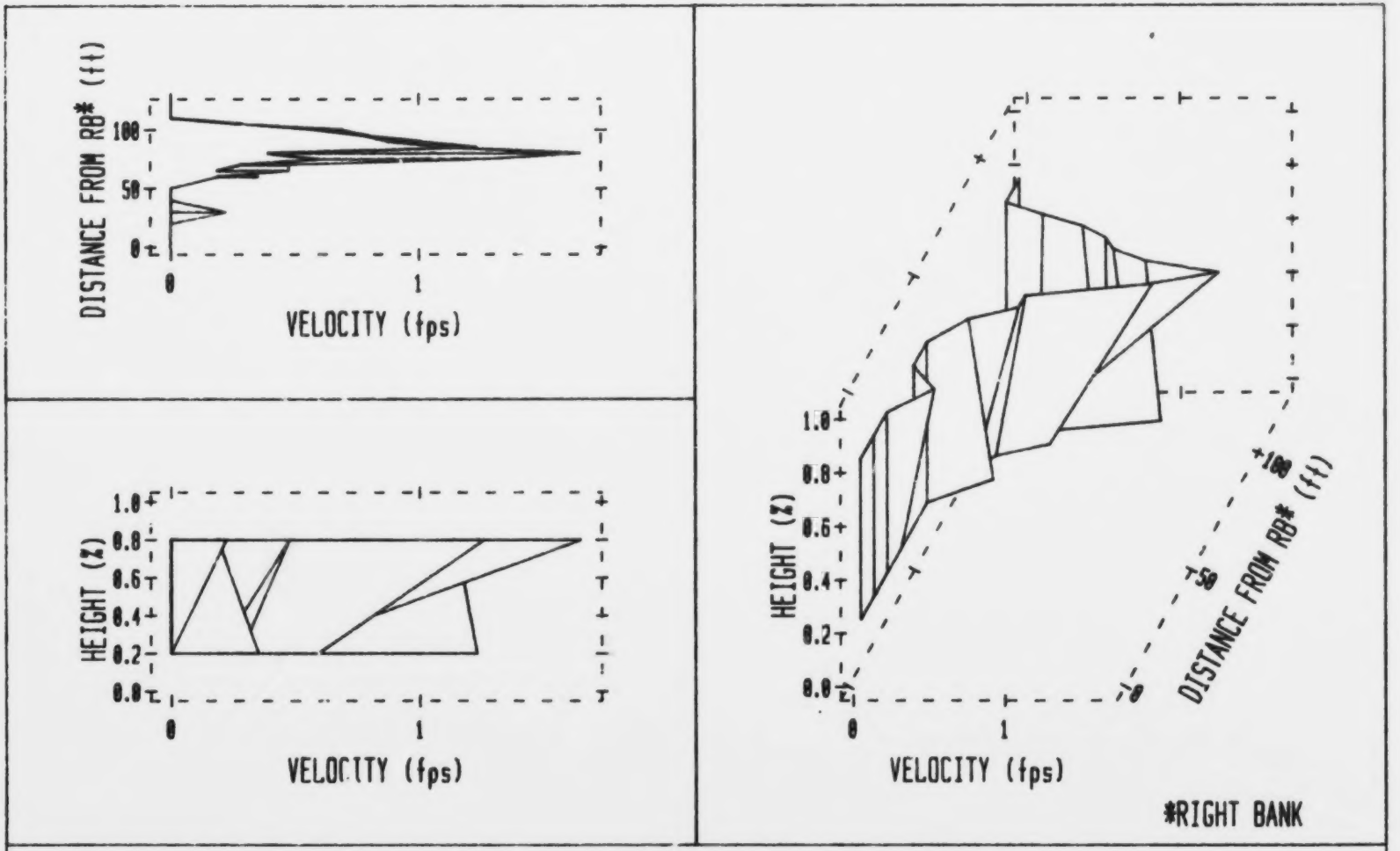

Figure 69. Velocity Distribution at Station 3+00 During Duck River Flow of 187 cfs.

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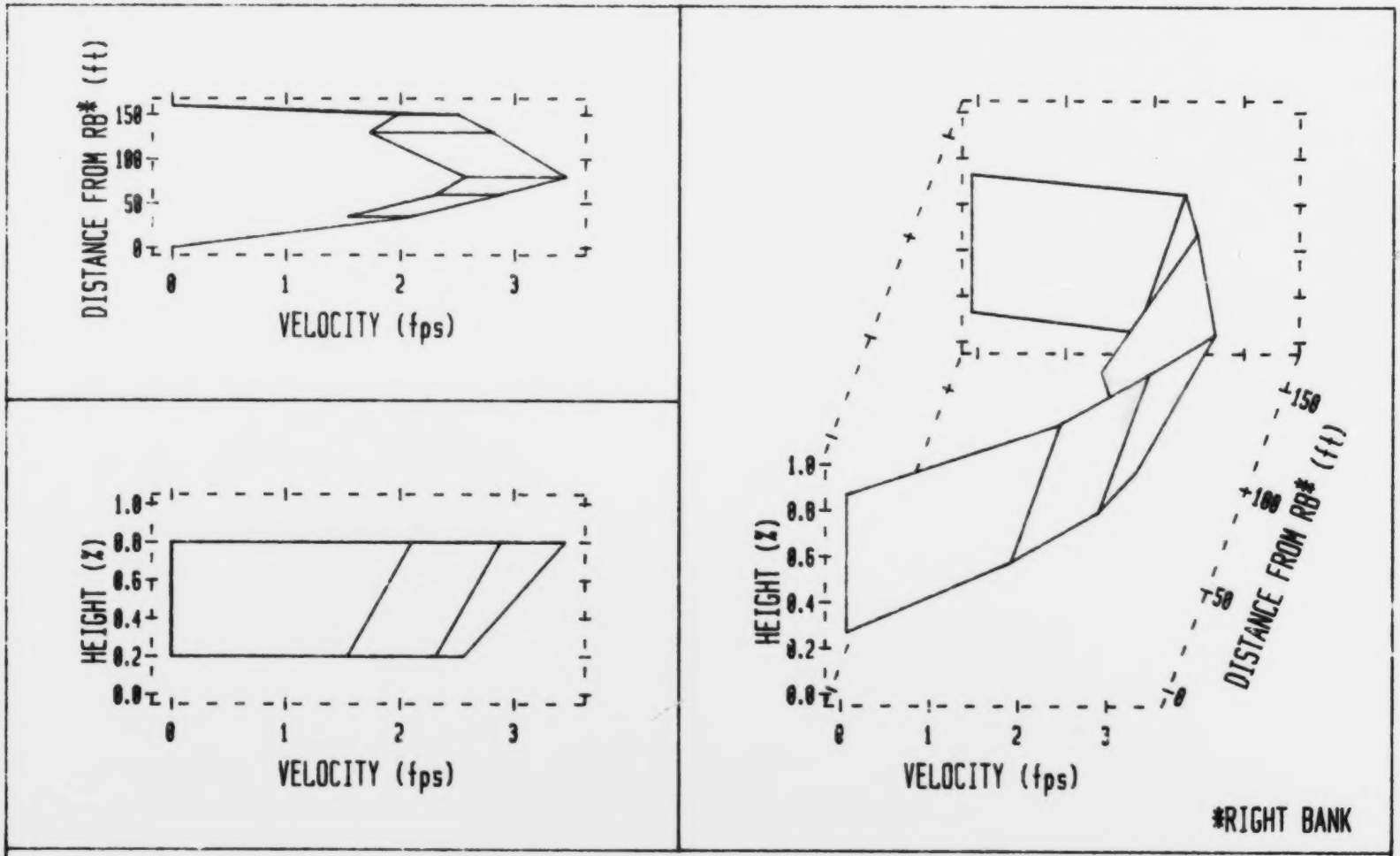

Figure 70. Velocity Distribution at Station 3+00 During Duck River Flow of 1731 cfs.

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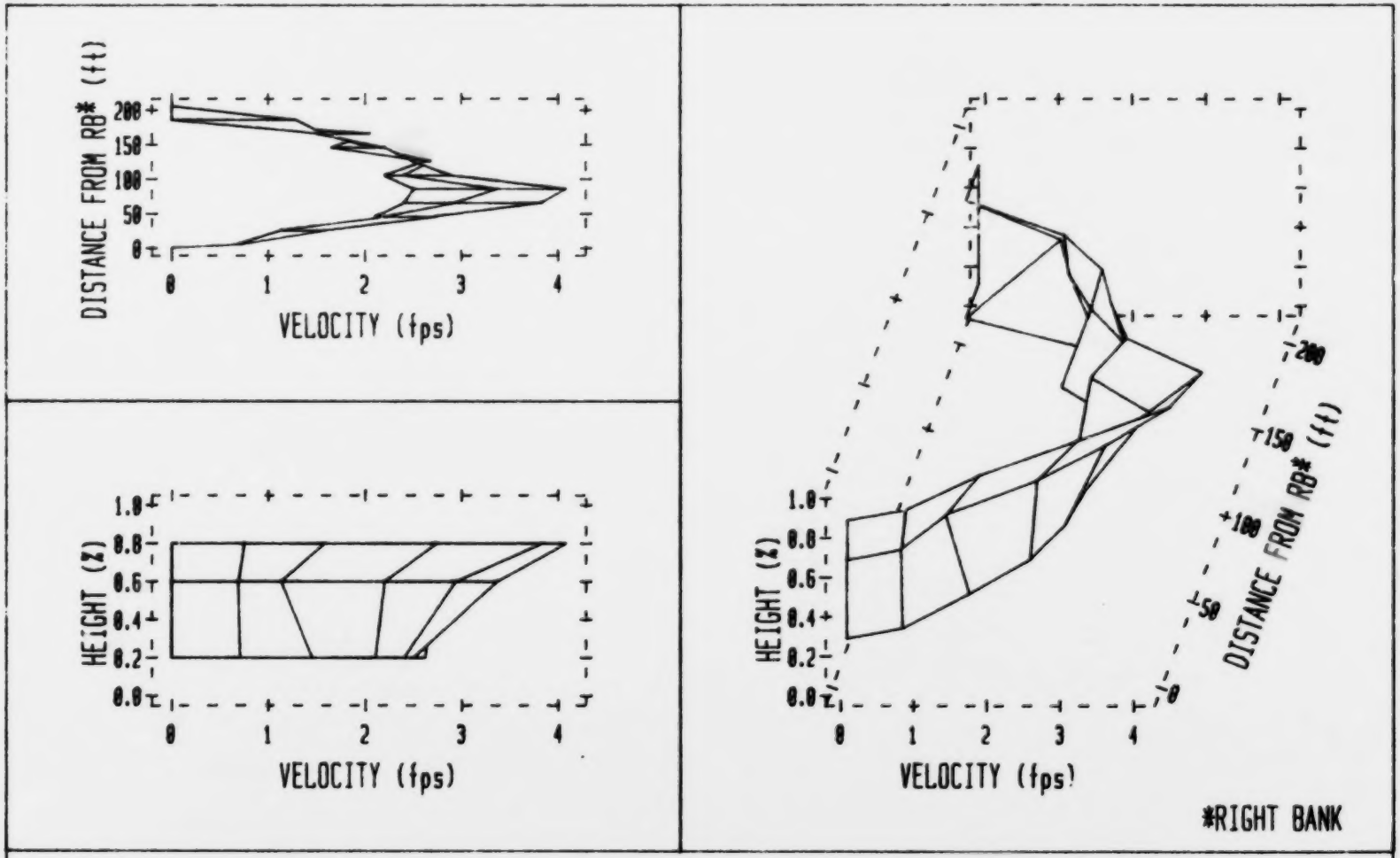

Figure 71. Velocity Distribution at Station 3+00 During Duck River Flow of 2366 cfs.

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APPENDIX A

STAGE-DISCHARGE RELATIONSHIPS - LOCATIONS OF SAMPLE POINTS FOR THE TASK I STUDY REACHES

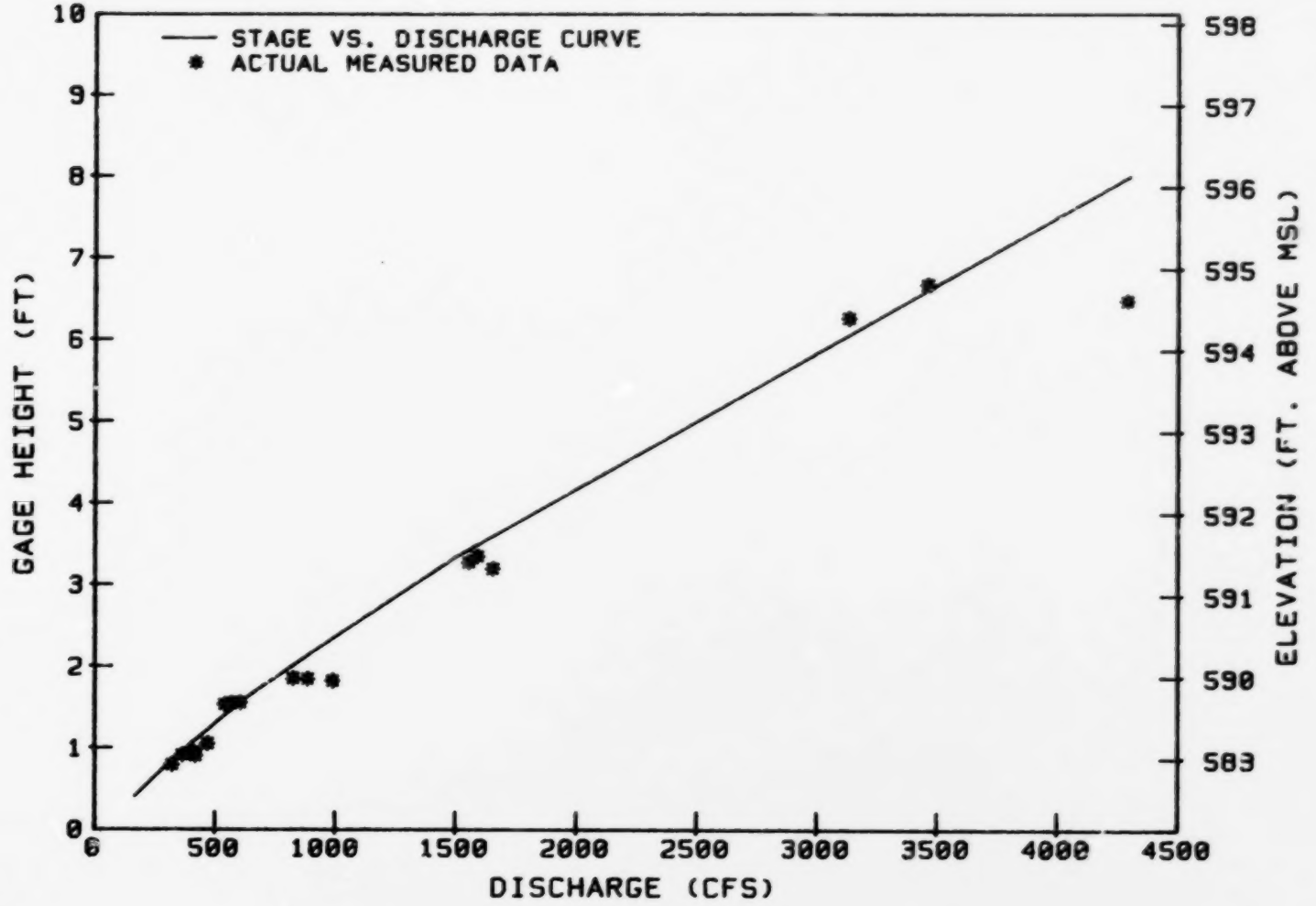

Figure A1. Stage-Discharge Relationship at Topsy Bridge, Buffalo River Mile 79.9.

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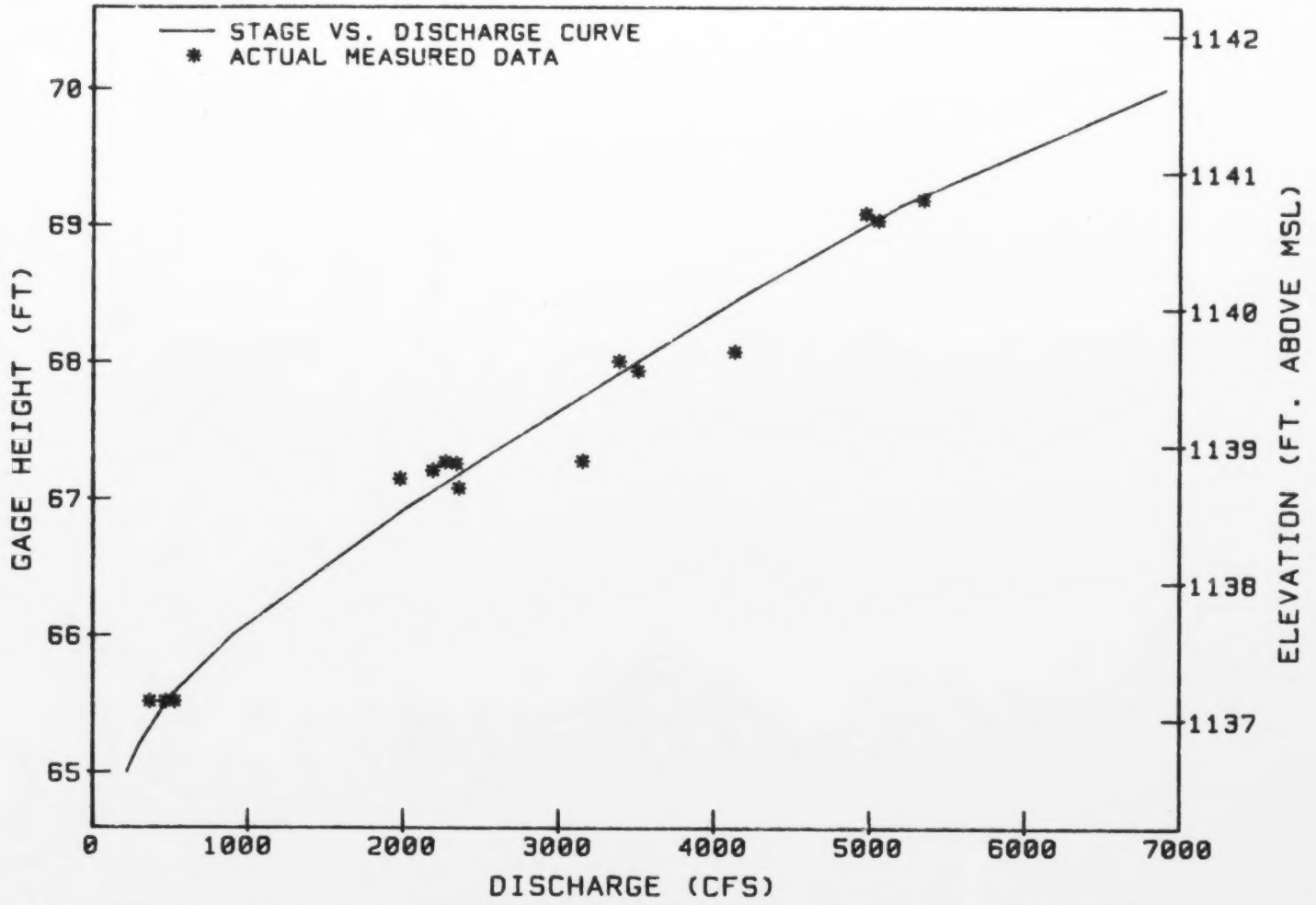

Figure A2. Stage-Discharge Relationship at Kyles Ford, Clinch River Mile 189.5

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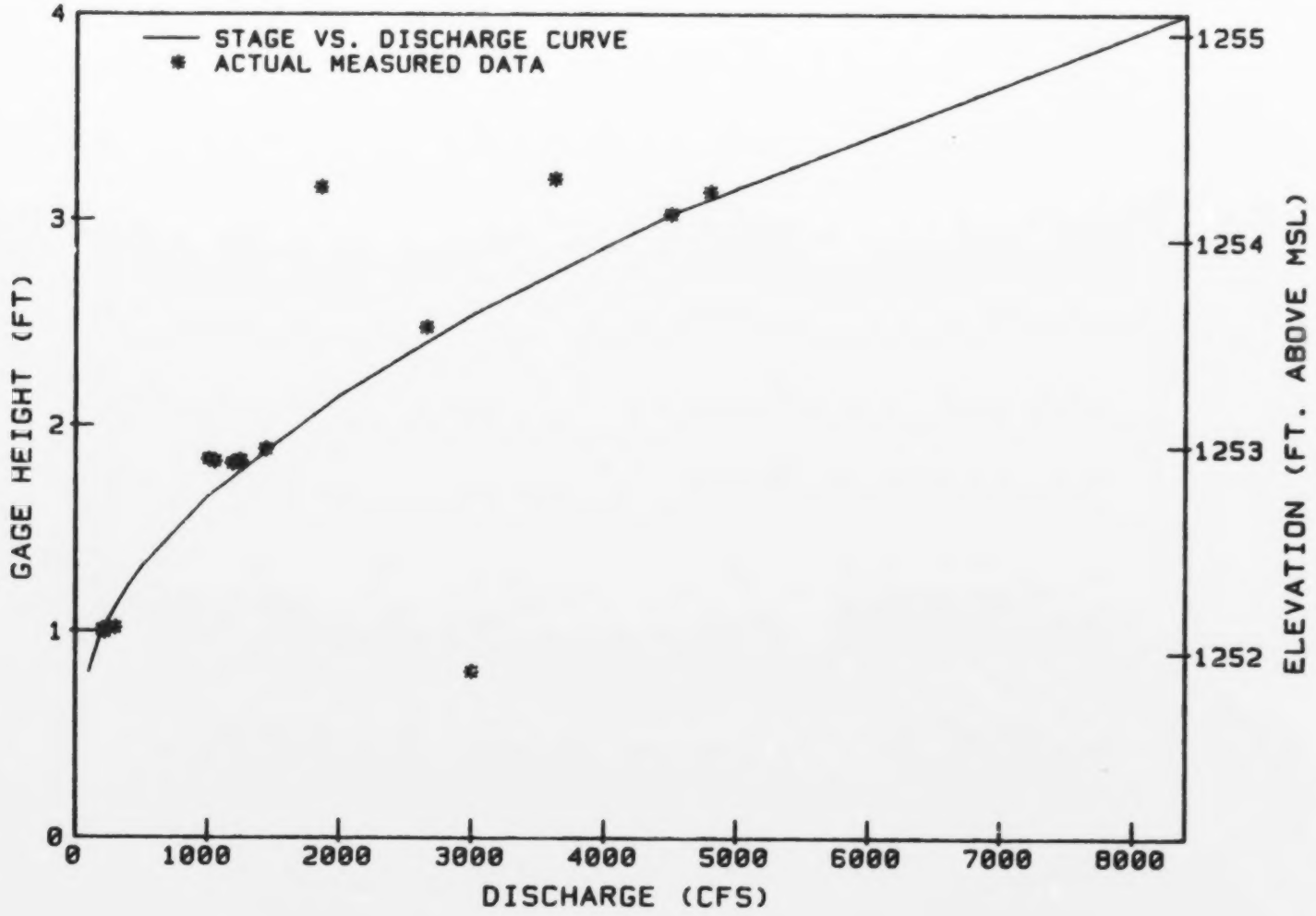

Figure A3. Stage-Discharge Relationship at Fort Blackmore, Clinch River Mile 227.4.

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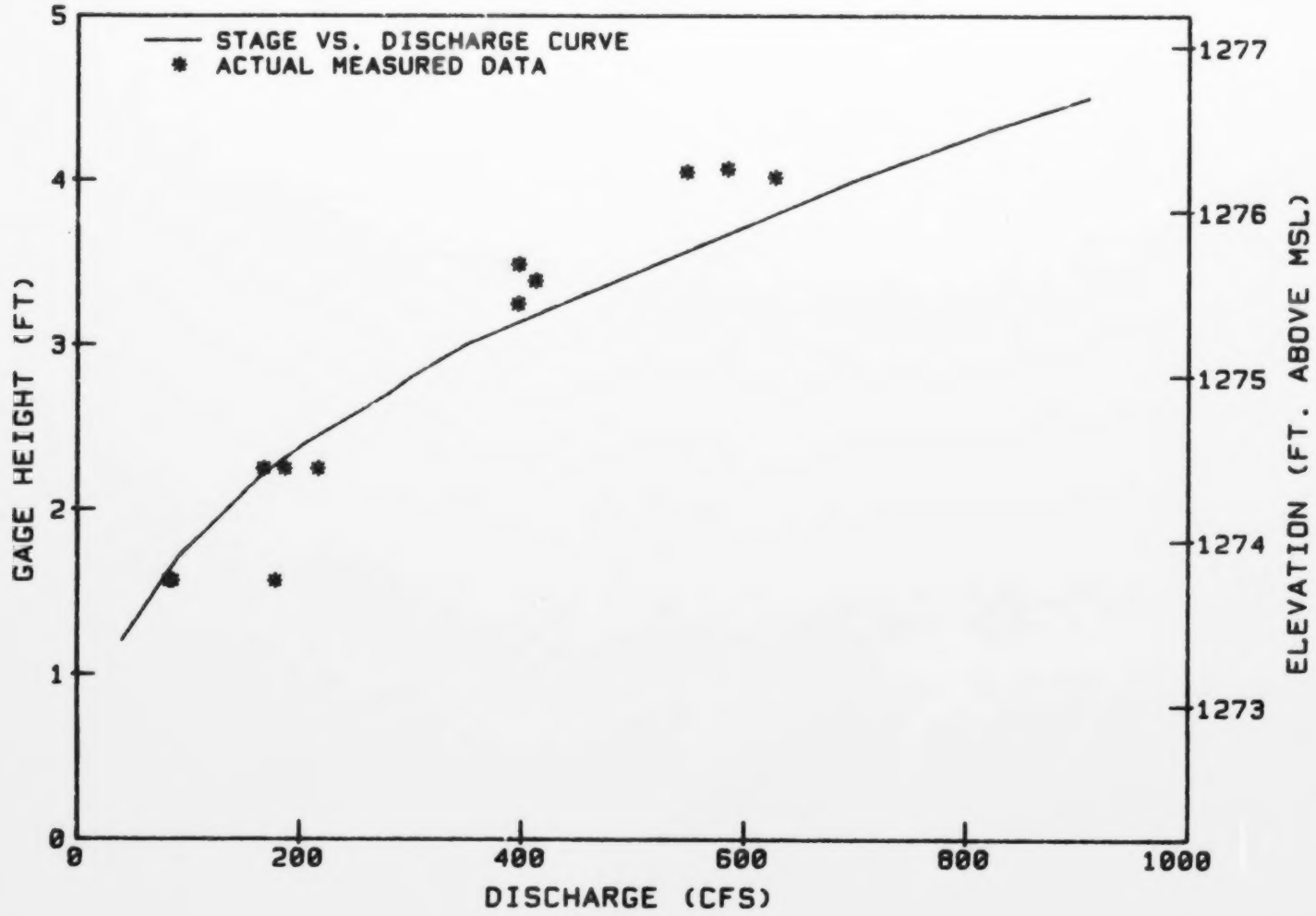

Figure A4. Stage-Discharge Relationship at Copper Creek Mile 1.9.

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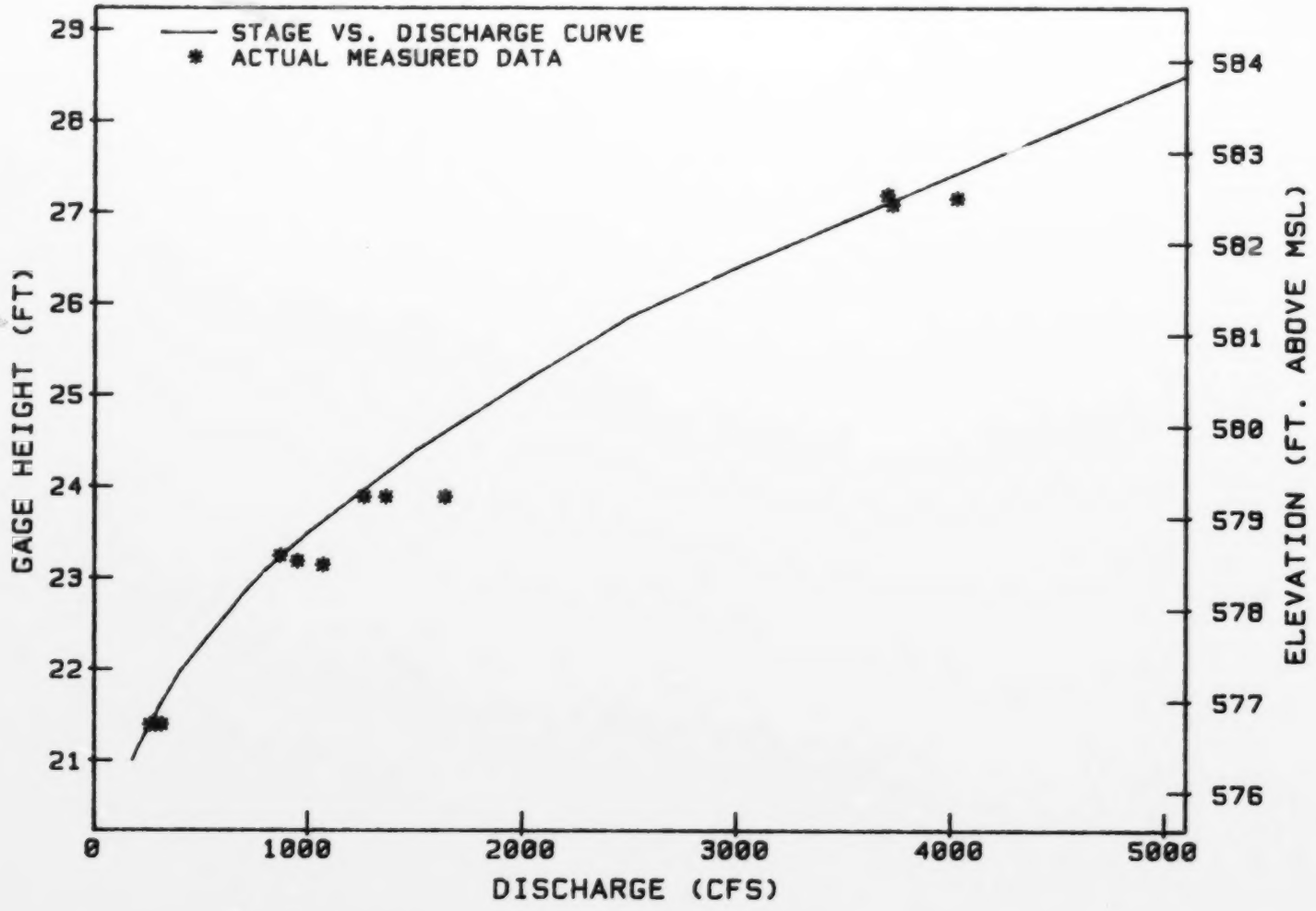

Figure A5. Stage-Discharge Relationship at Sowell Ford, Duck River Mile 159.4.

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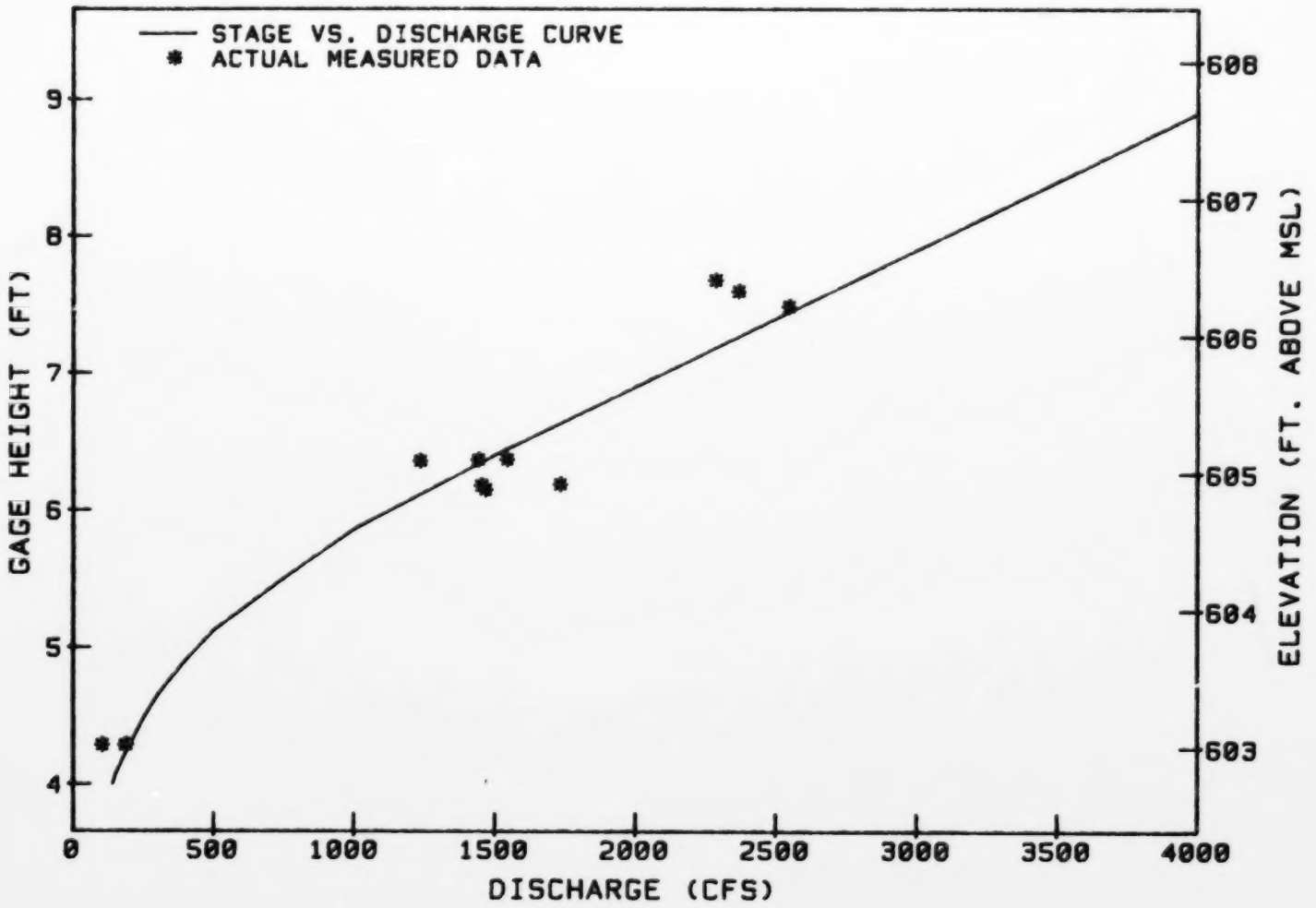

Figure A6. Stage-Discharge Relationship at Lillard Mill, Duck River Mile 179.1.

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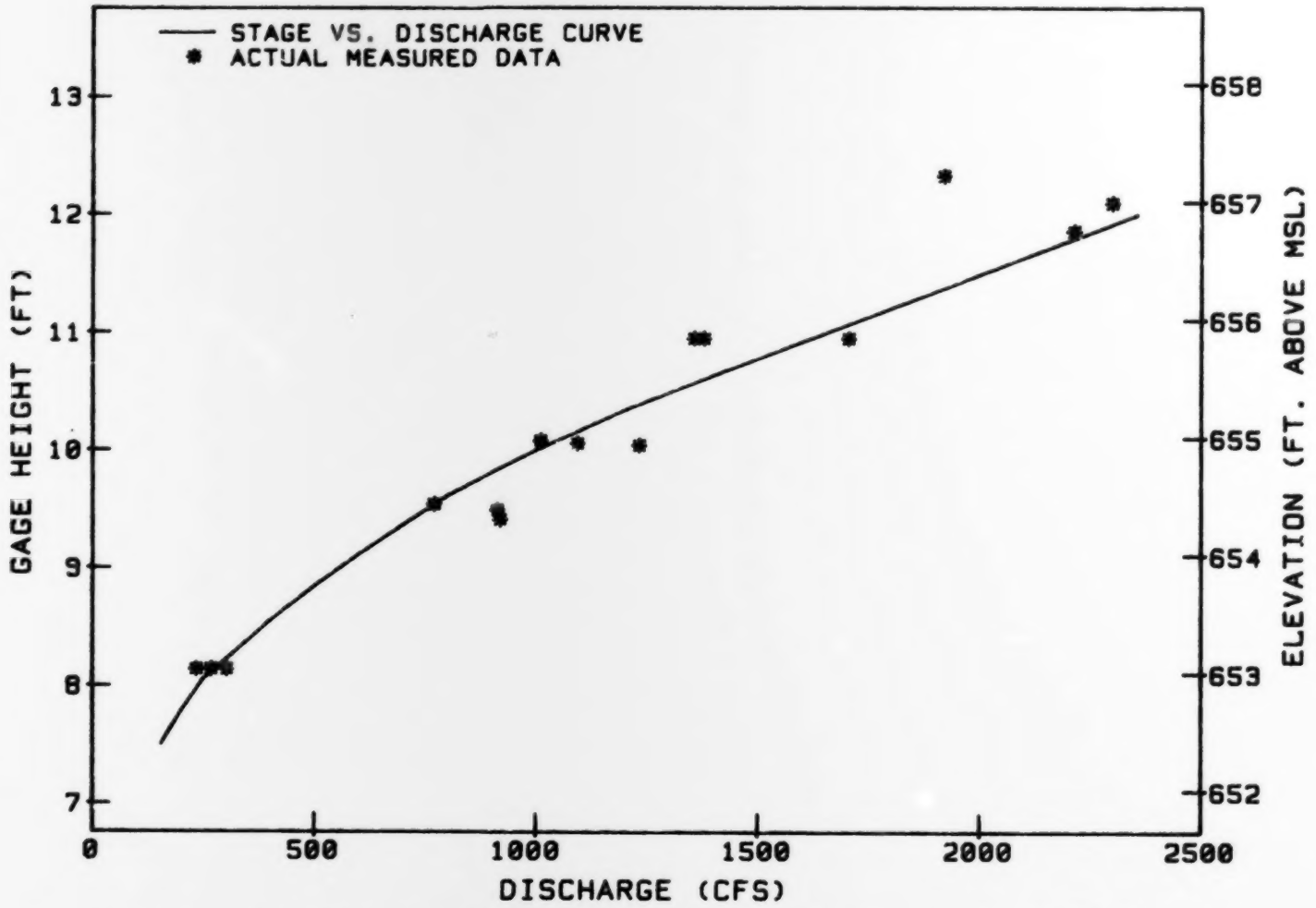

Figure A7. Stage-Discharge Relationship at Hall's Mill, Duck River Mile 202.2.

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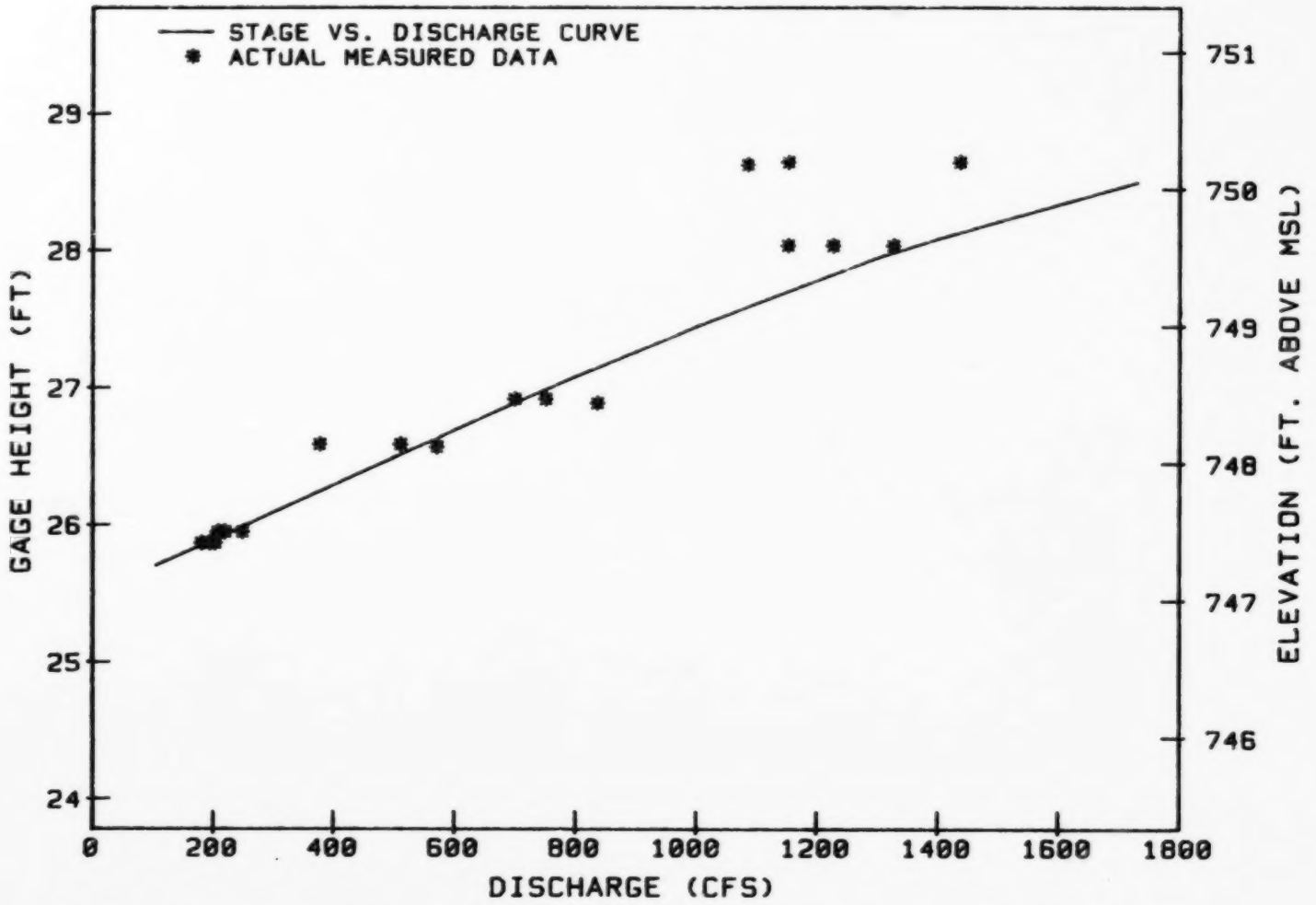

Figure A8. Stage-Discharge Relationship at Dement Bridge, Duck River Mile 243.1.

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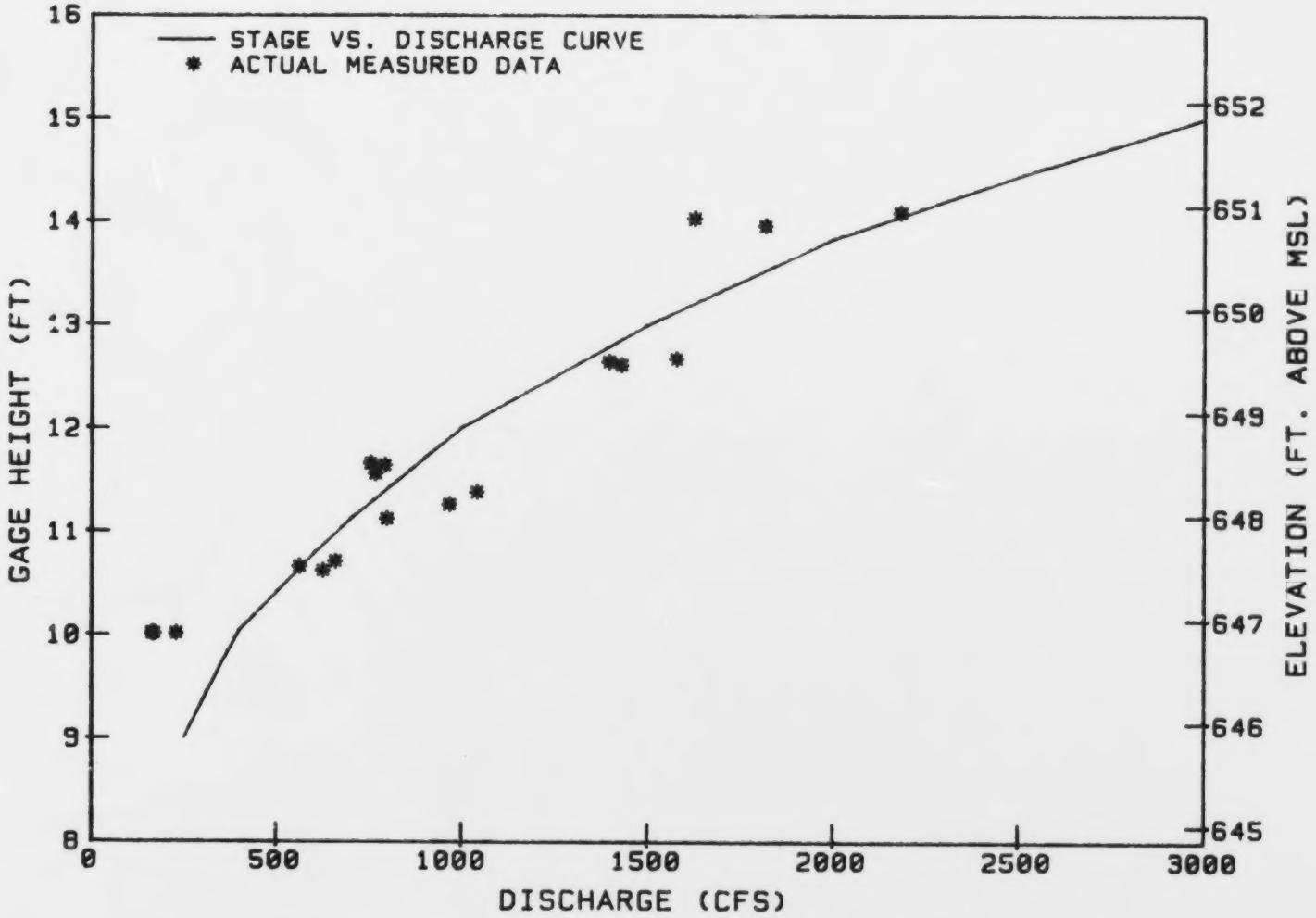

Figure A9. Stage-Discharge Relationship at Elk River Mile 91.4.

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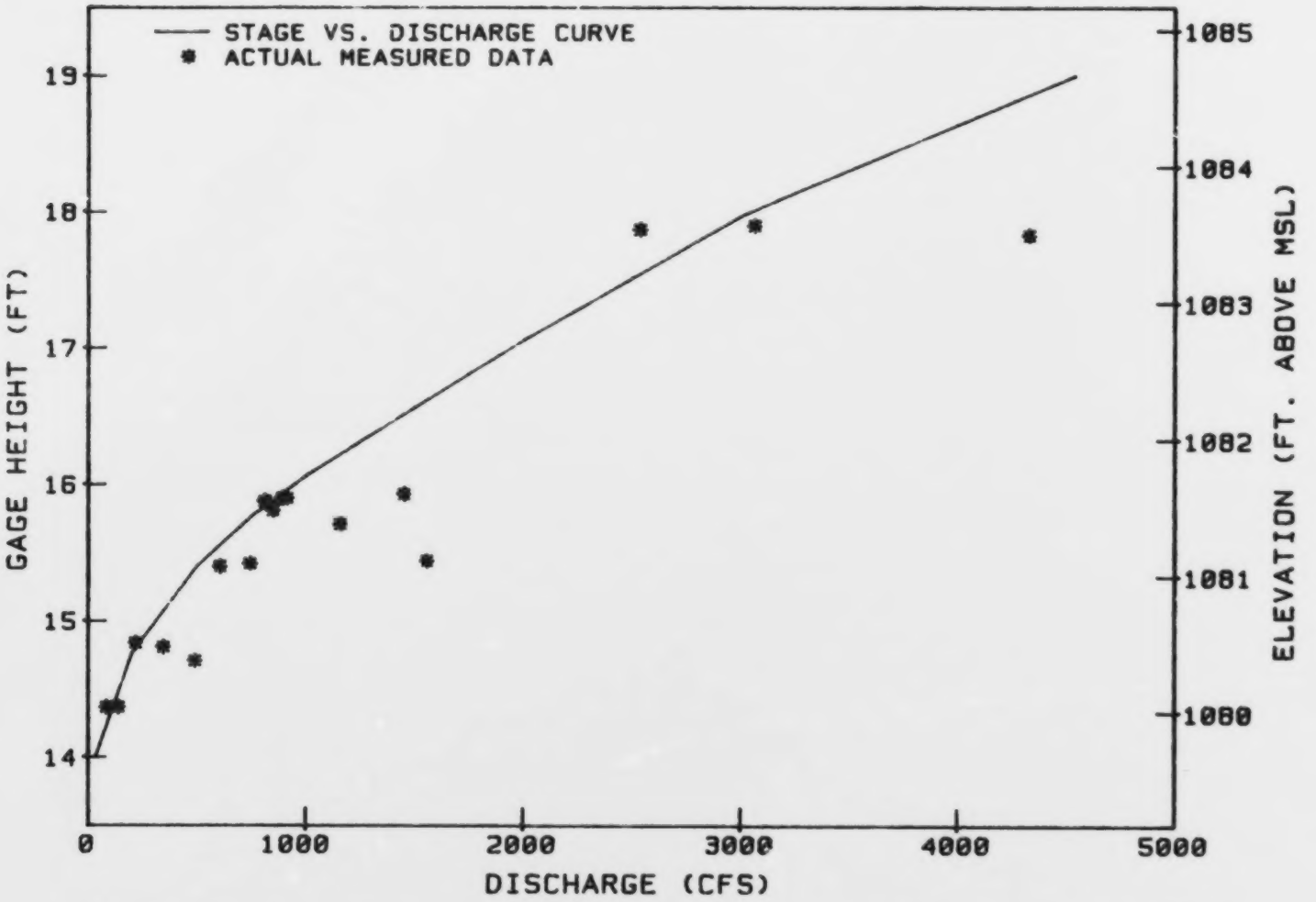

Figure A10. Stage-Discharge Relationship at Hale Bridge, Nolichucky River Mile 27.8.

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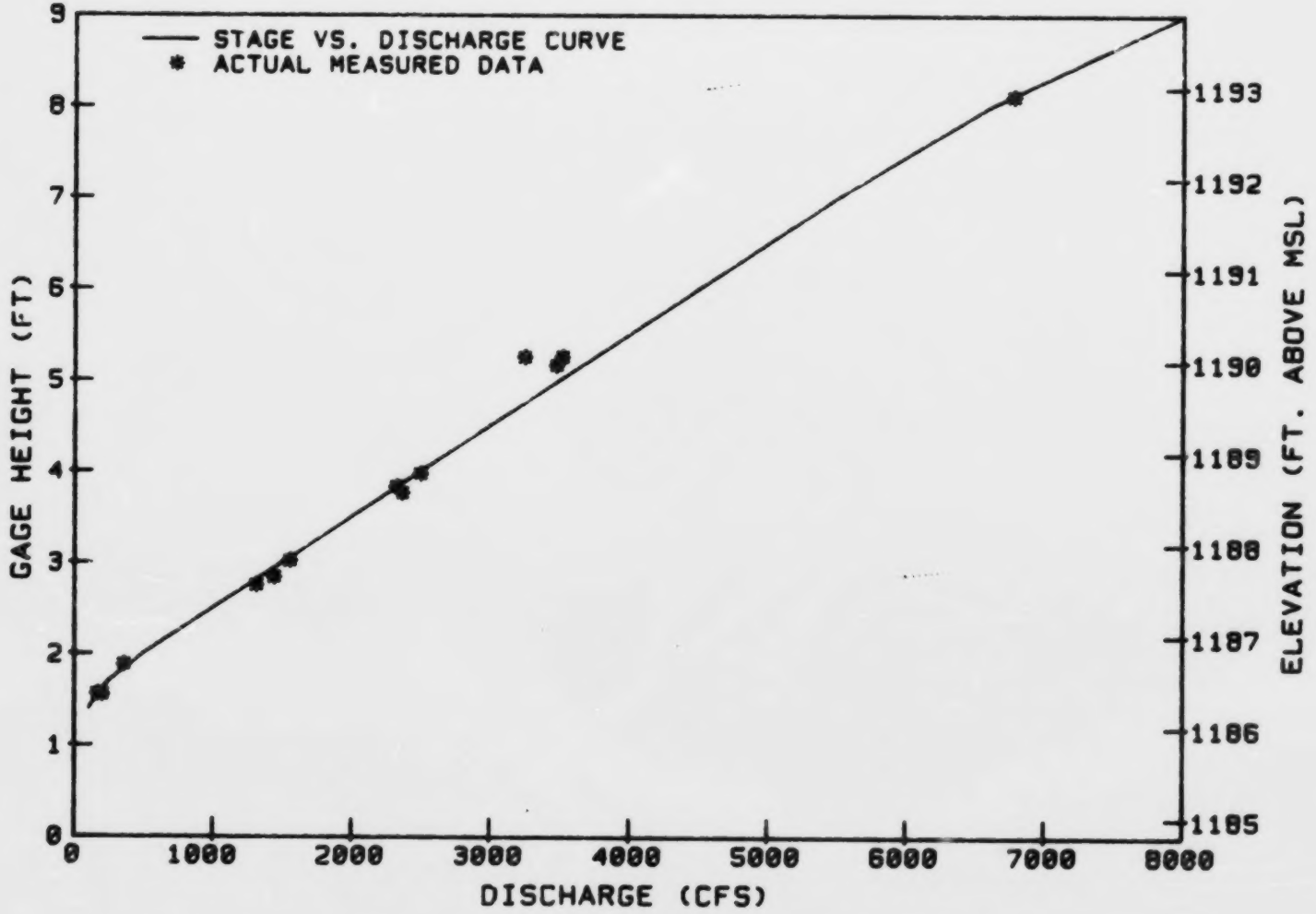

Figure A11. Stage-Discharge Relationship at Click Island, North Fork Holston River Mile 6.2.

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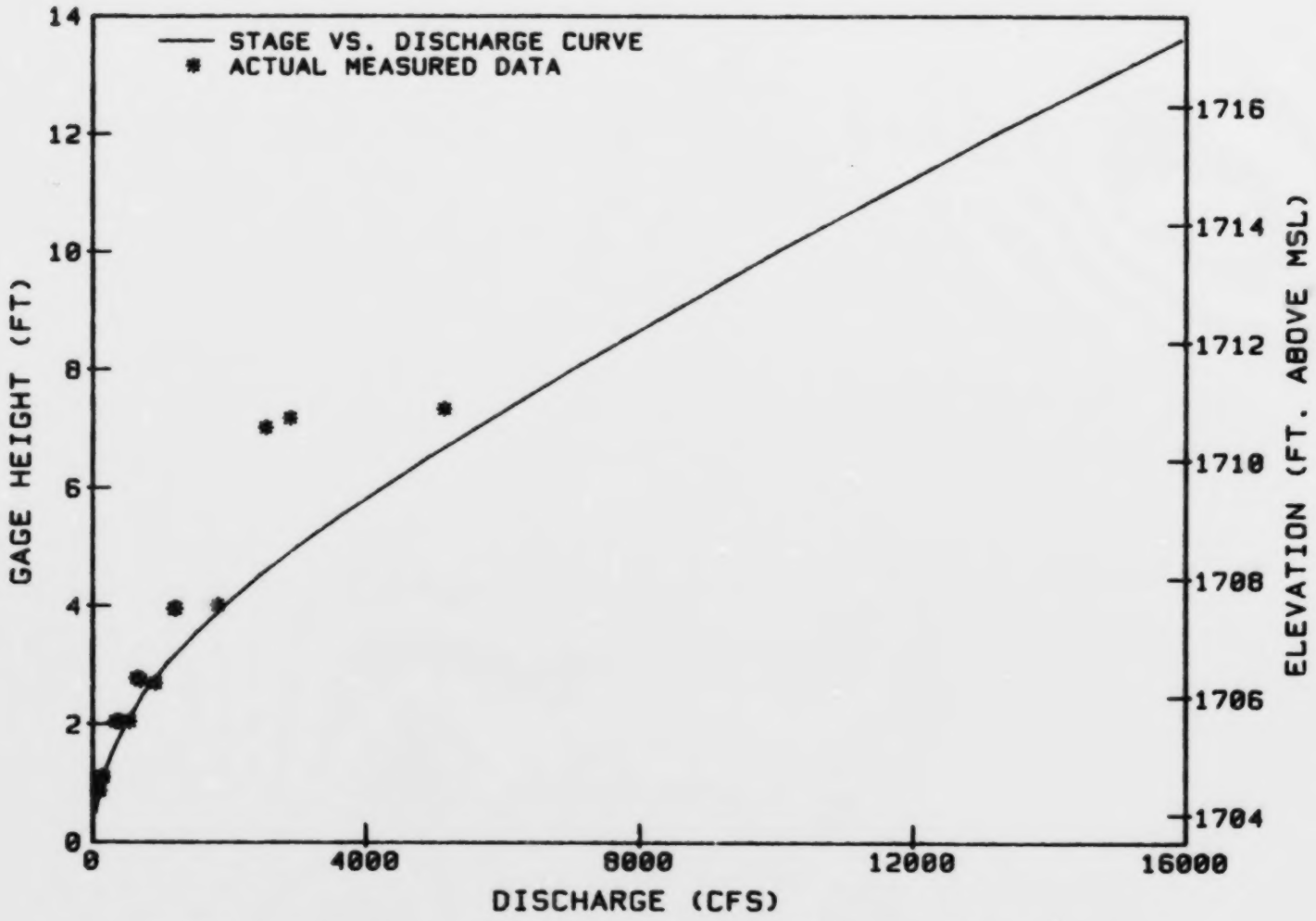

Figure A12. Stage-Discharge Relationship at Saltville, North Fork Holston River Mile 85.2.

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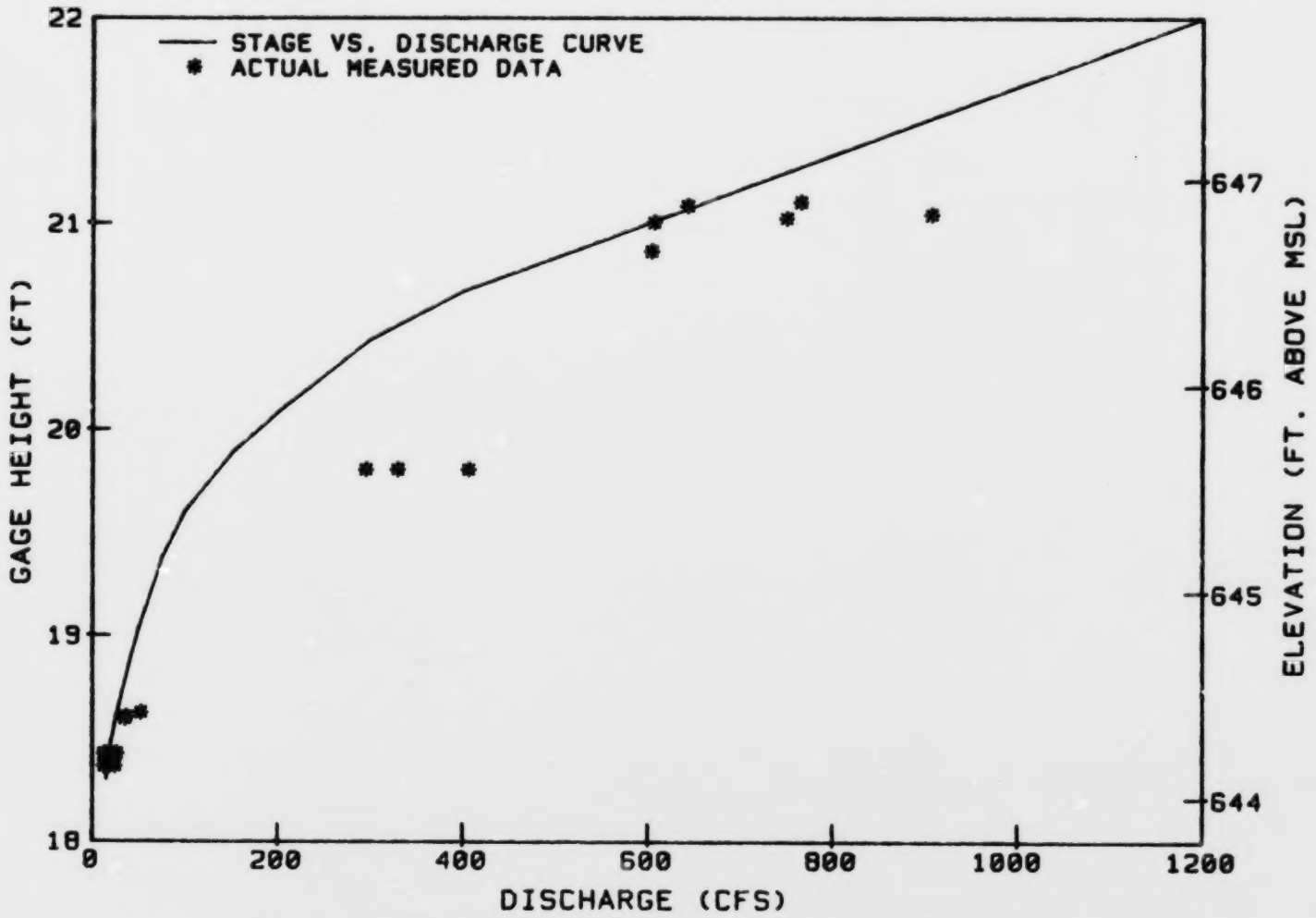

Figure A13. Stage-Discharge Relationship at Estill Fork, Paint Rock River Mile 60.0.

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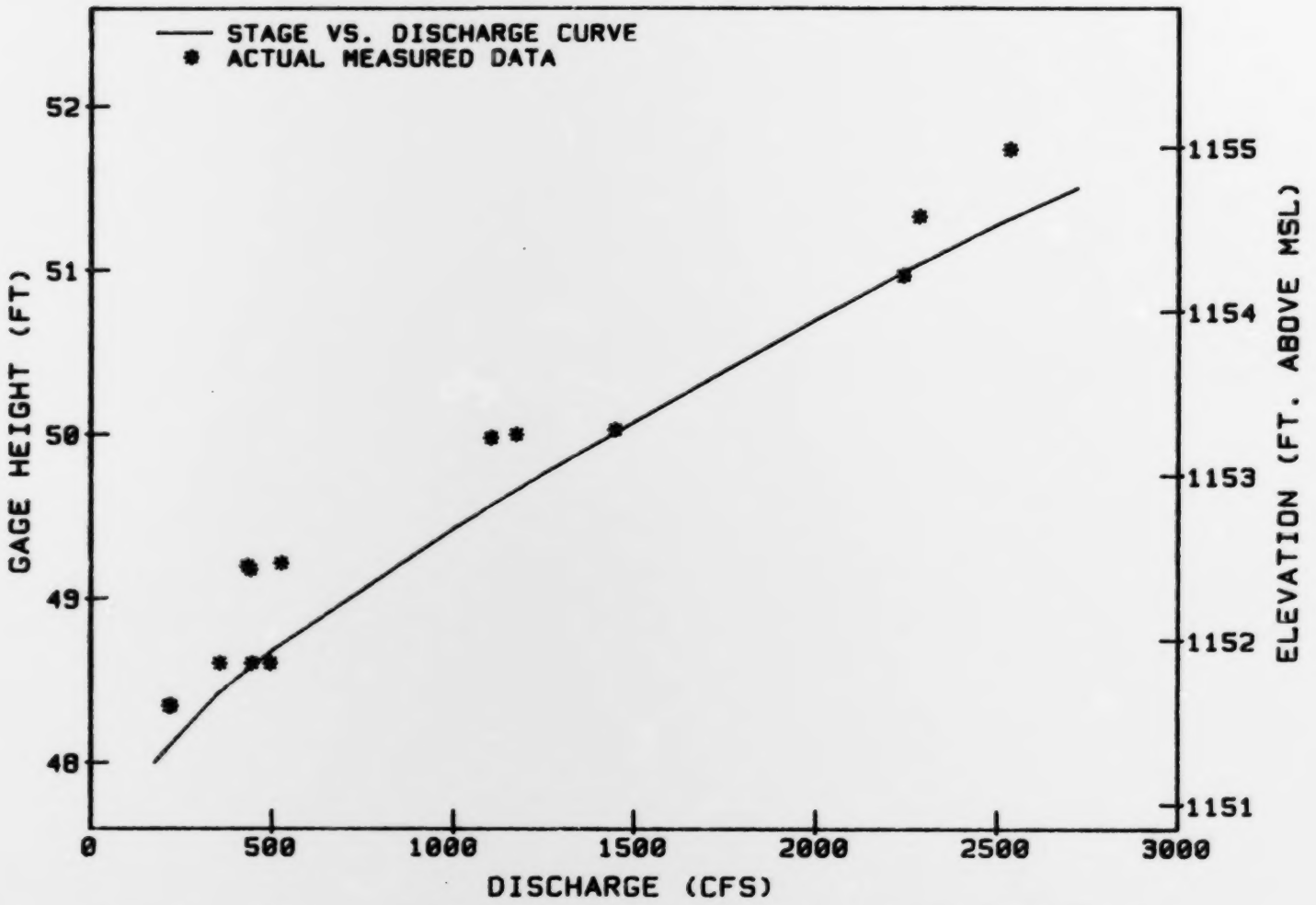

Figure A14. Stage-Discharge Relationship at Buchanan Ford, Powell River Mile 99.2.

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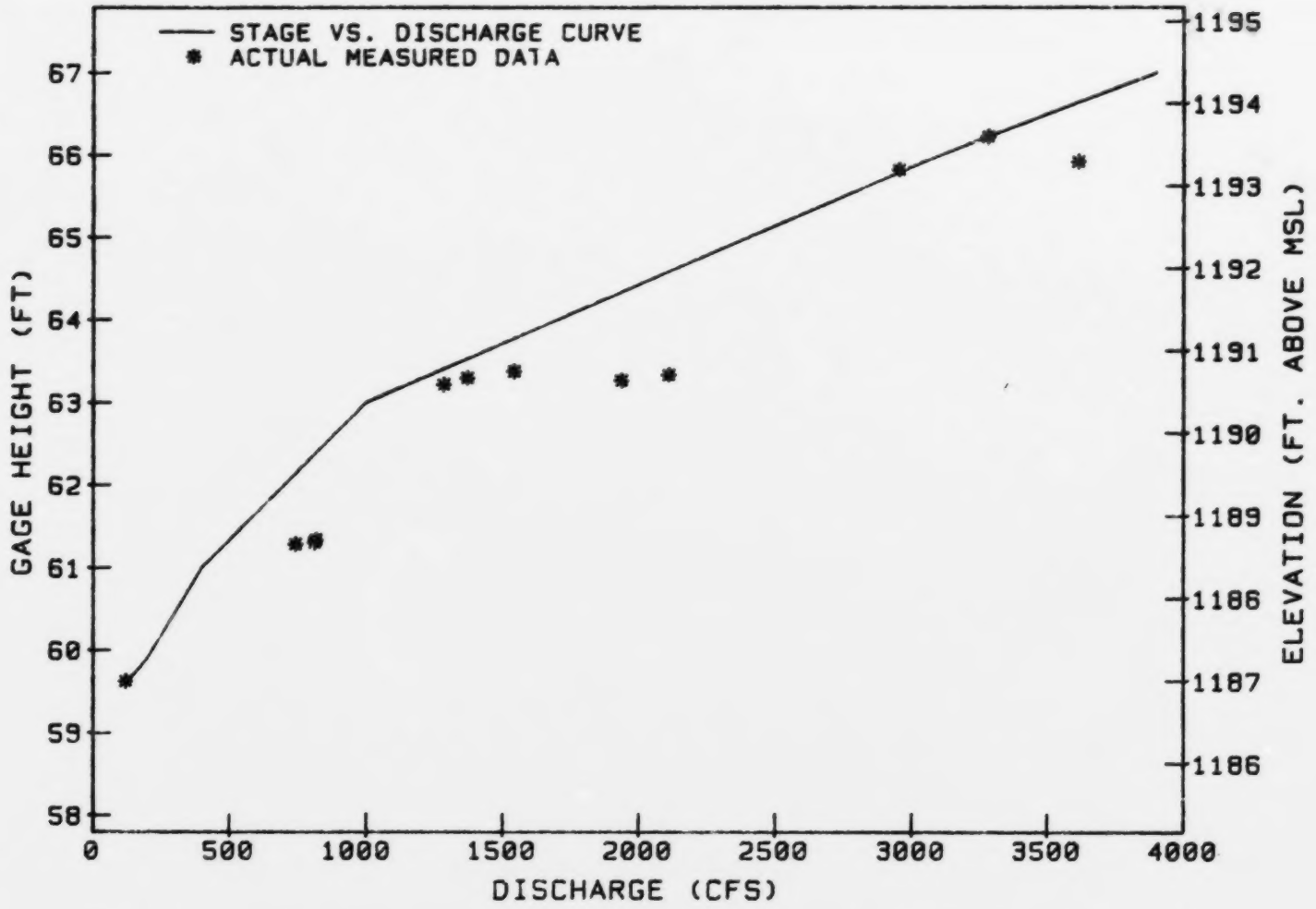

Figure A15. Stage-Discharge Relationship at Fletcher Ford, Powell River Mile 117.4.

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APPENDIX B

FLOW DURATION CURVES FOR TASK I STUDY REACHES

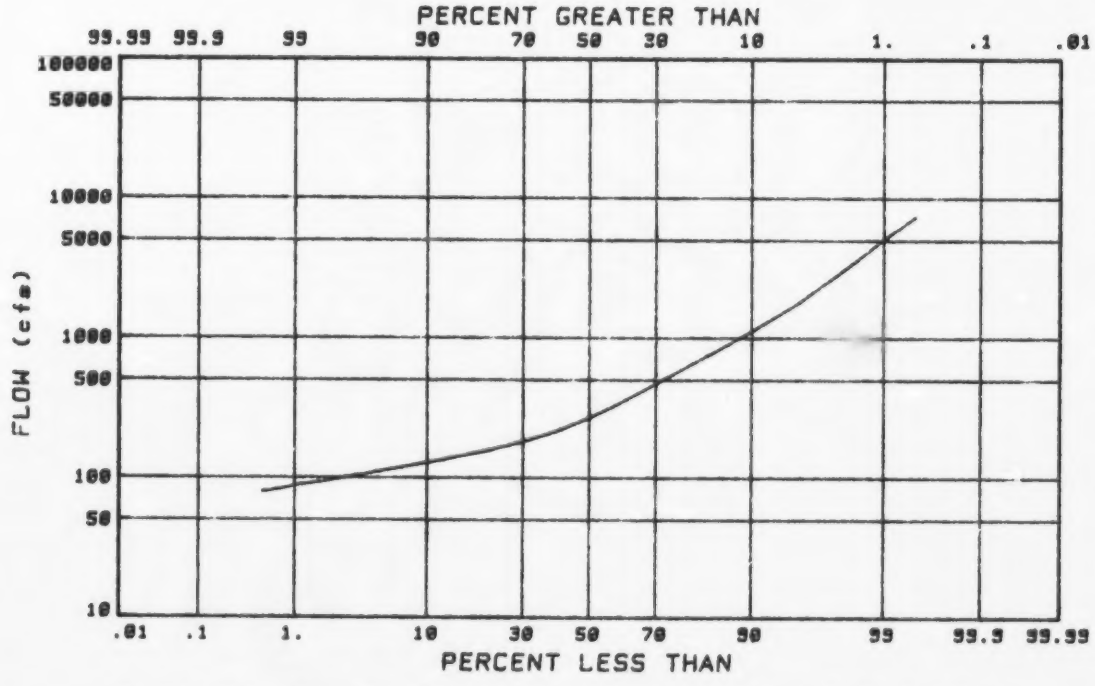

Figure B1. Flow Duration Curve at Topsy Bridge, Buffalo River Mile 79.9.

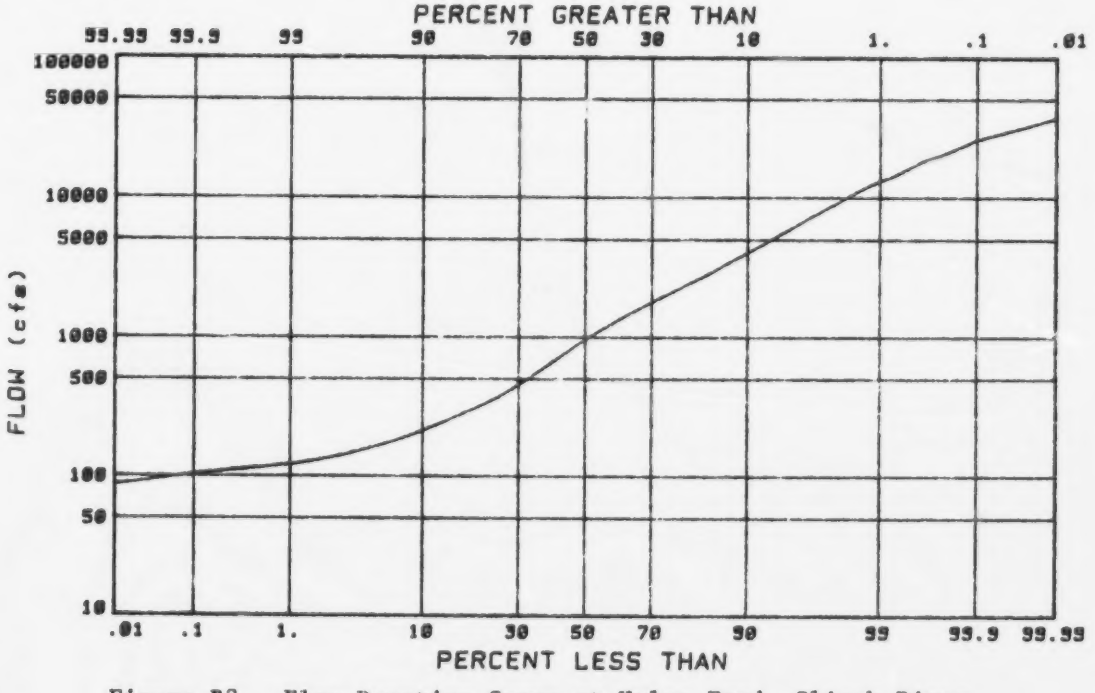

Figure B2. Flow Duration Curve at Kyles Ford, Clinch River Mile 189.5.

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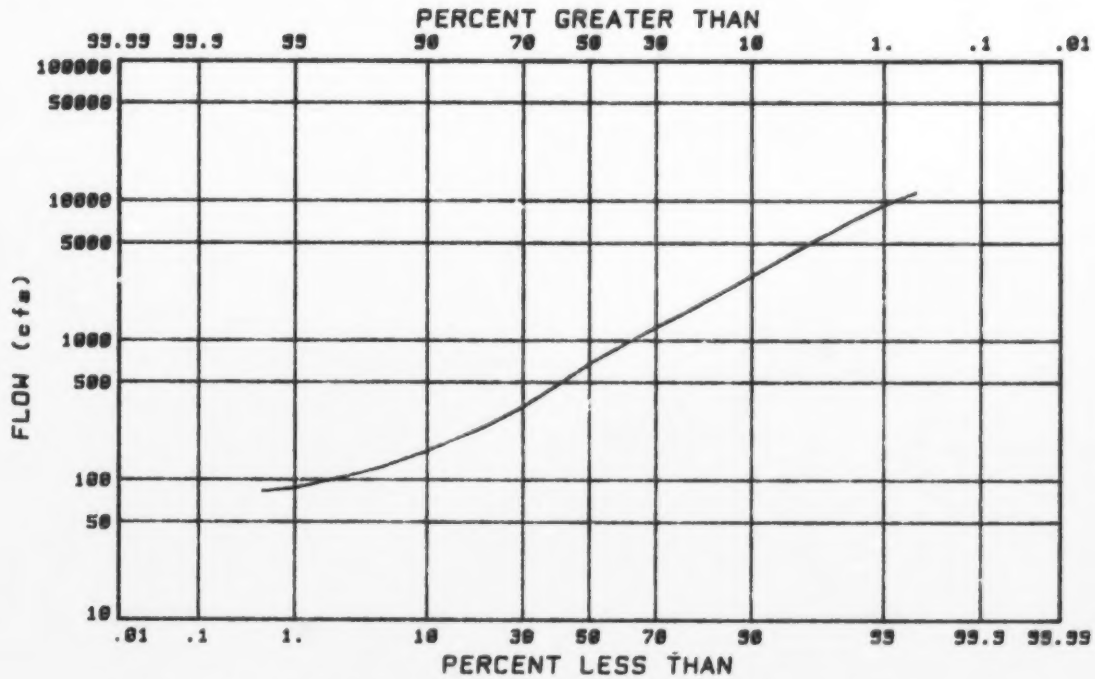

Figure B3. Flow Duration Curve at Fort Blackmore, Clinch River Mile 227.4.

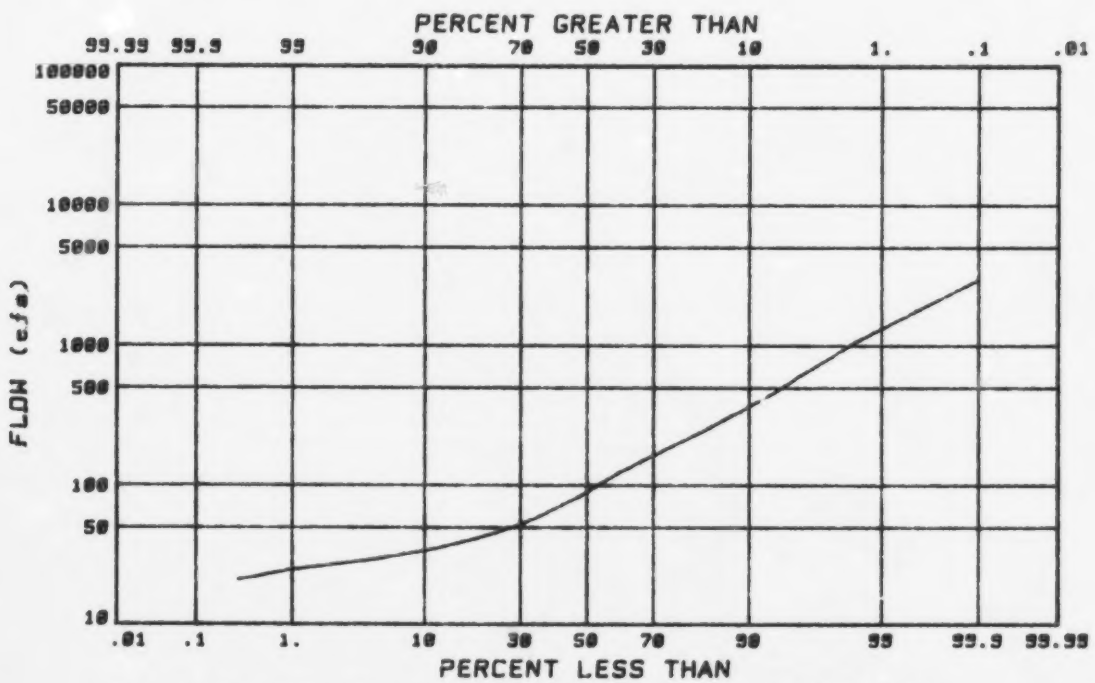

Figure B4. Flow Duration Curve at Copper Creek Mile 1.9.

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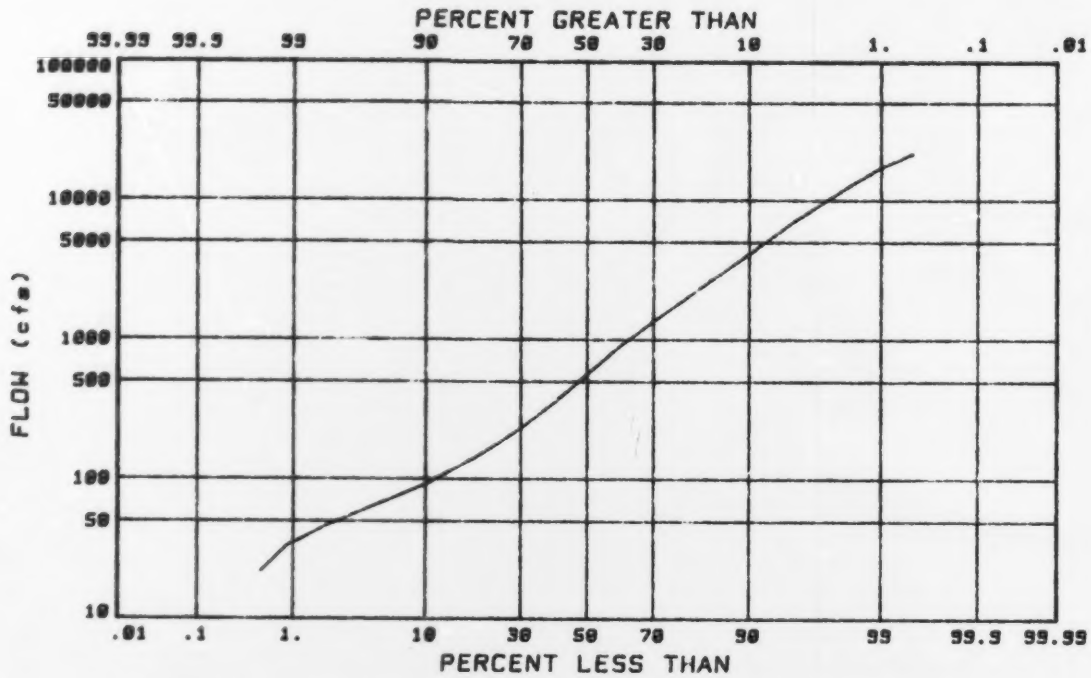

Figure B5. Flow Duration Curve at Sowell Ford, Duck River Mile 159.4.

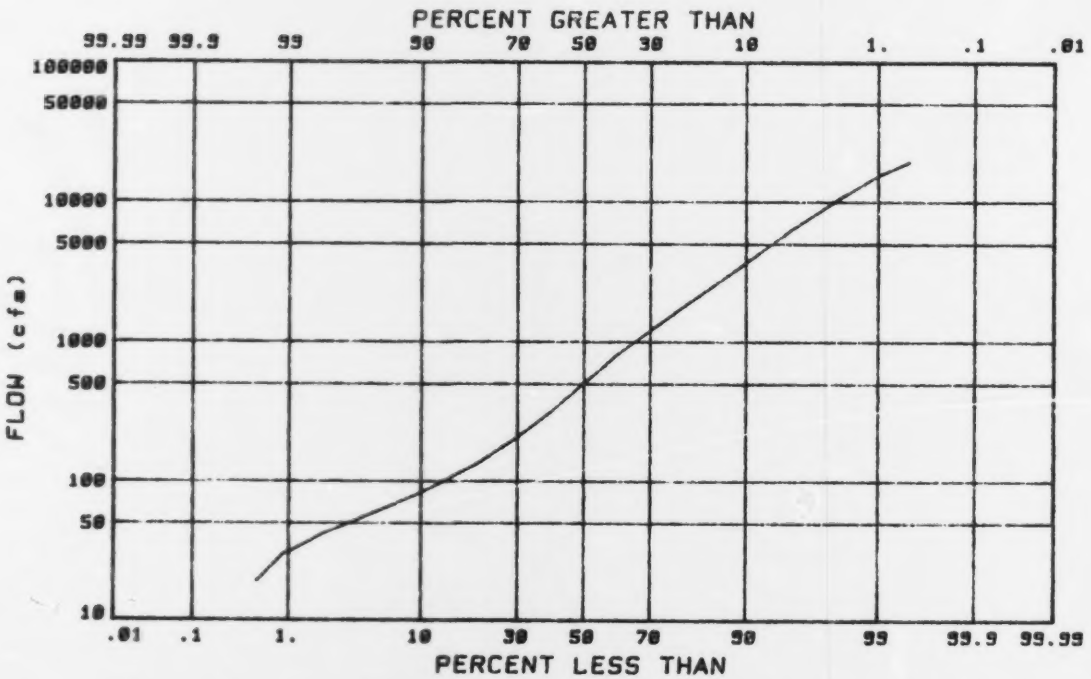

Figure B6. Flow Duration Curve at Lillard Mill, Duck River Mile 179.1.

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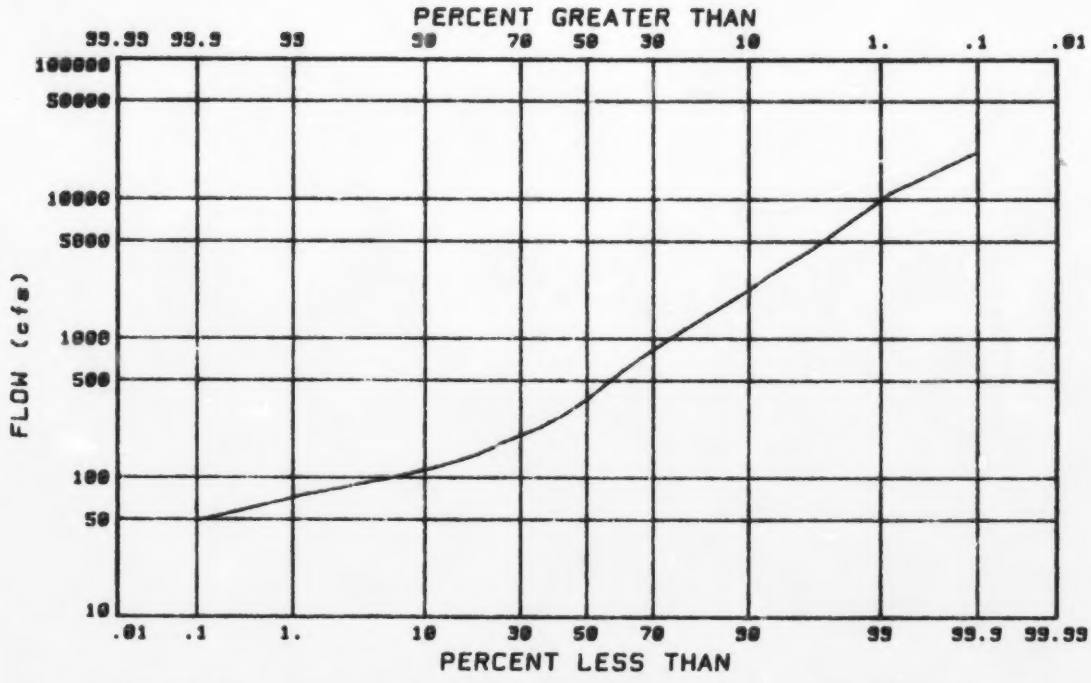

Figure B7. Flow Duration Curve at Halls Mill, Duck River Mile 202.2.

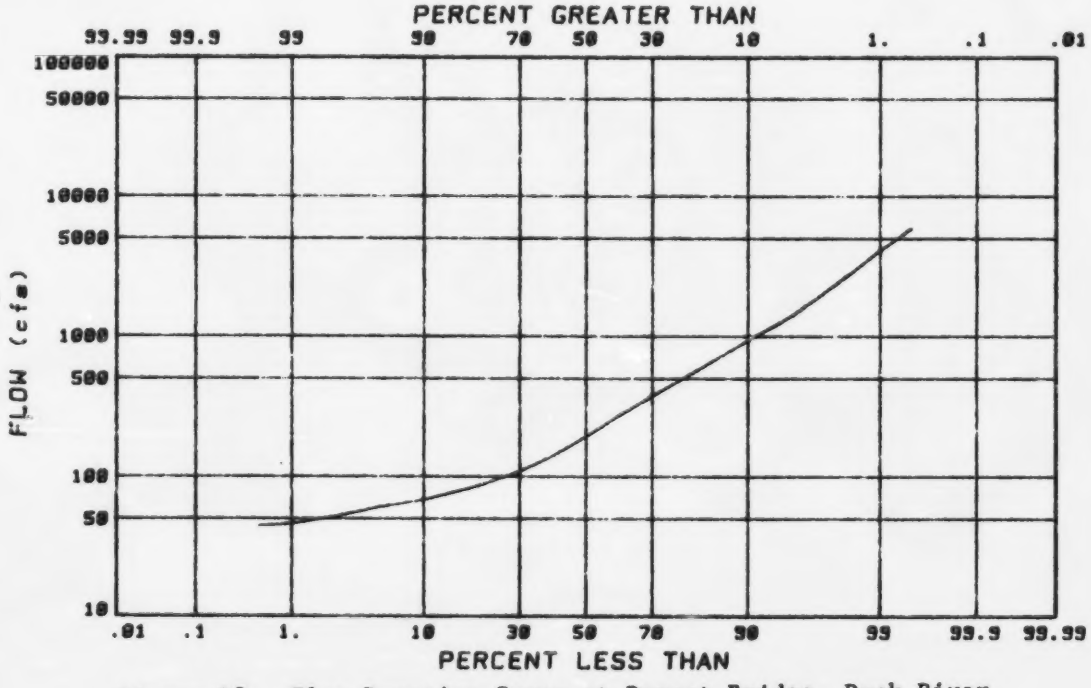

Figure B8. Flow Duration Curve at Dement Bridge, Duck River Mile 243.1.

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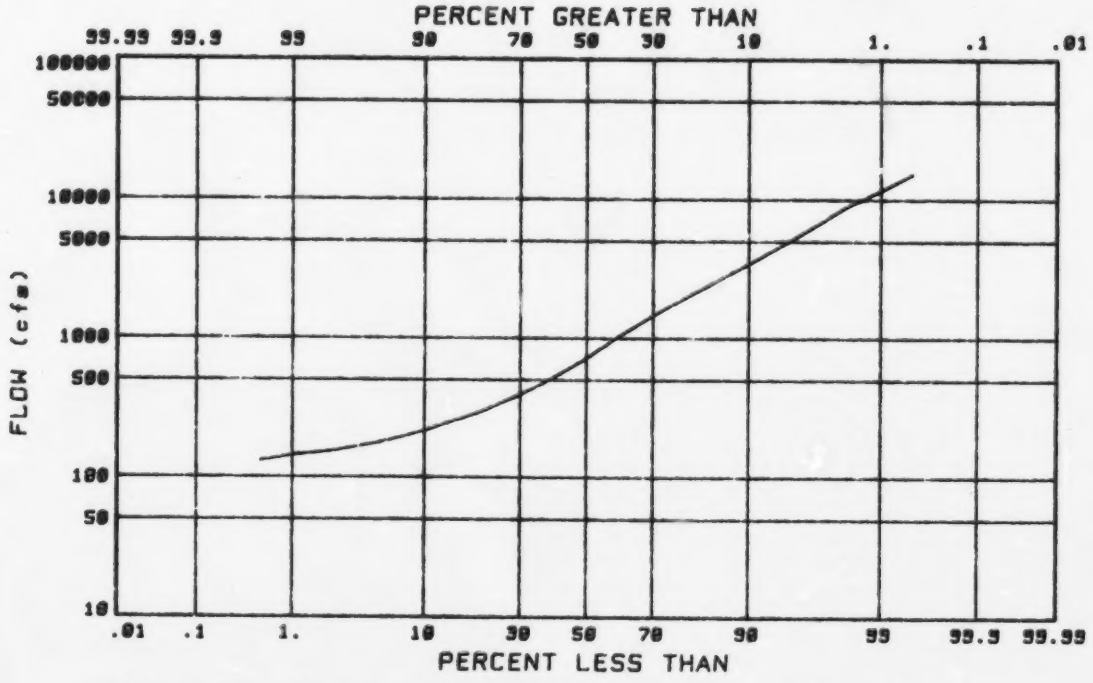

Figure B9. Flow Duration Curve at Elk River Mile 91.4.

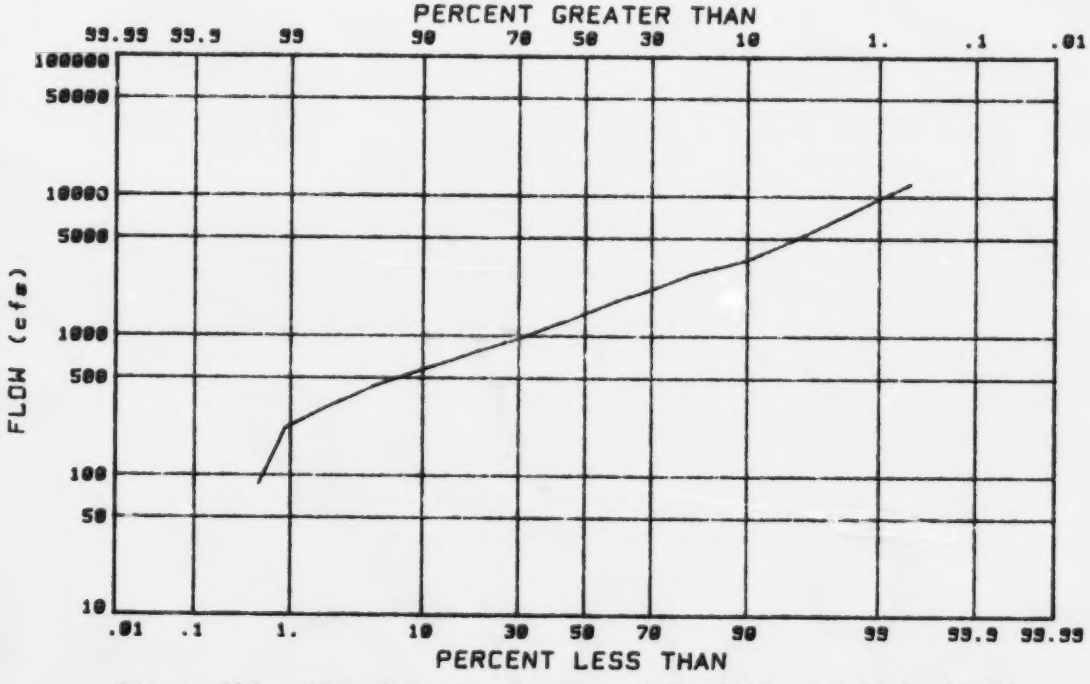

Figure B10. Flow Duration Curve at Hale Bridge, Nolichucky River Mile 27.8.

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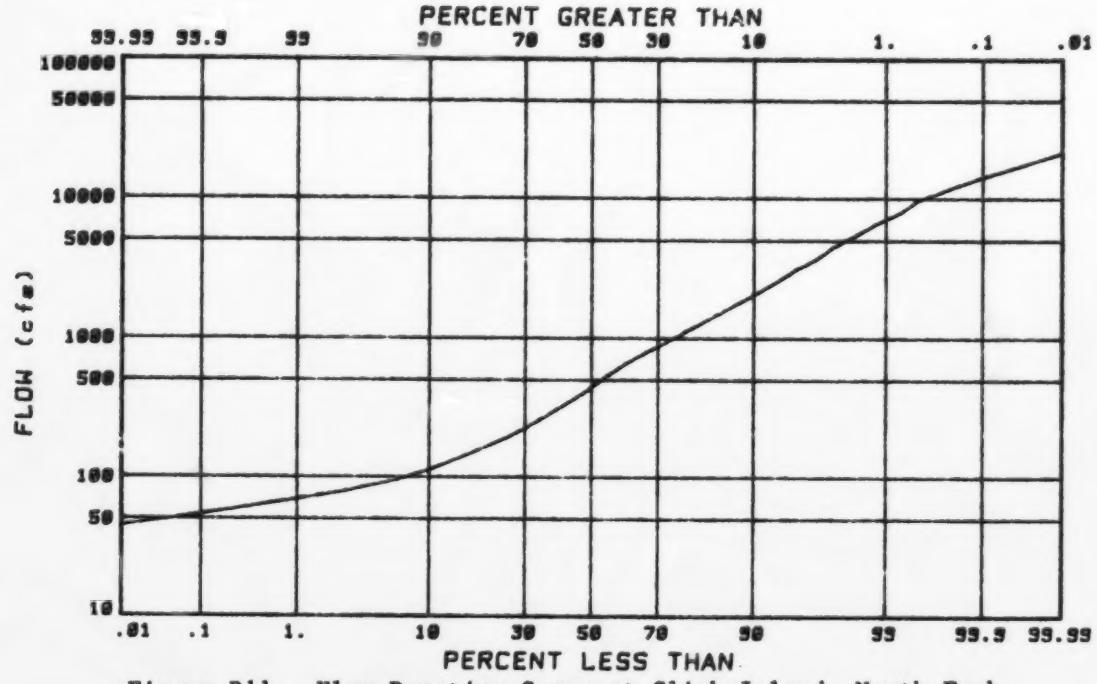

Figure B11. Flow Duration Curve at Click Island, North Fork Holston River Mile 6.2.

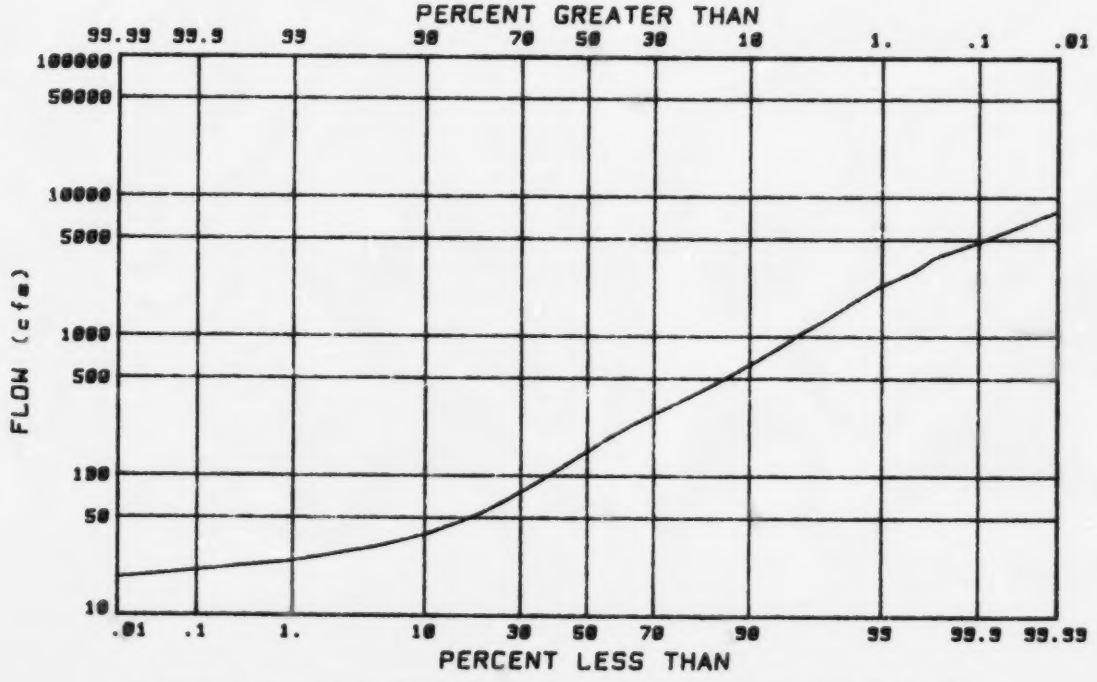

Figure B12. Flow Duration Curve at Saltville, North Fork Holston River Mile 85.2.

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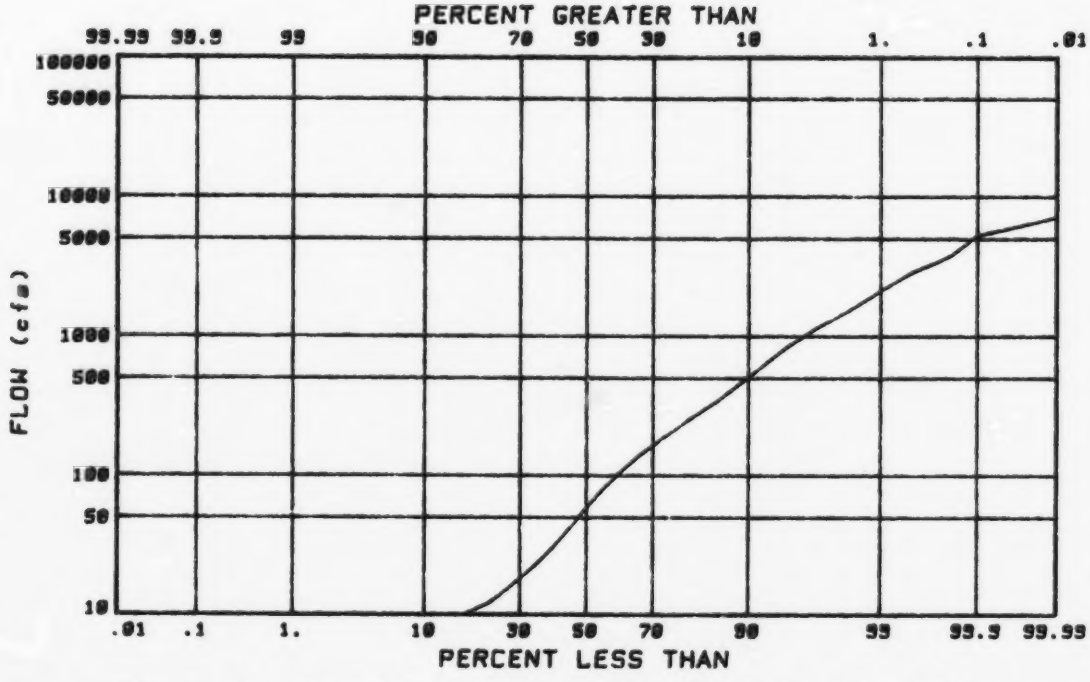

Figure B13. Flow Duration Curve at Estill Fork, Paint Rock River Mile 60.0.

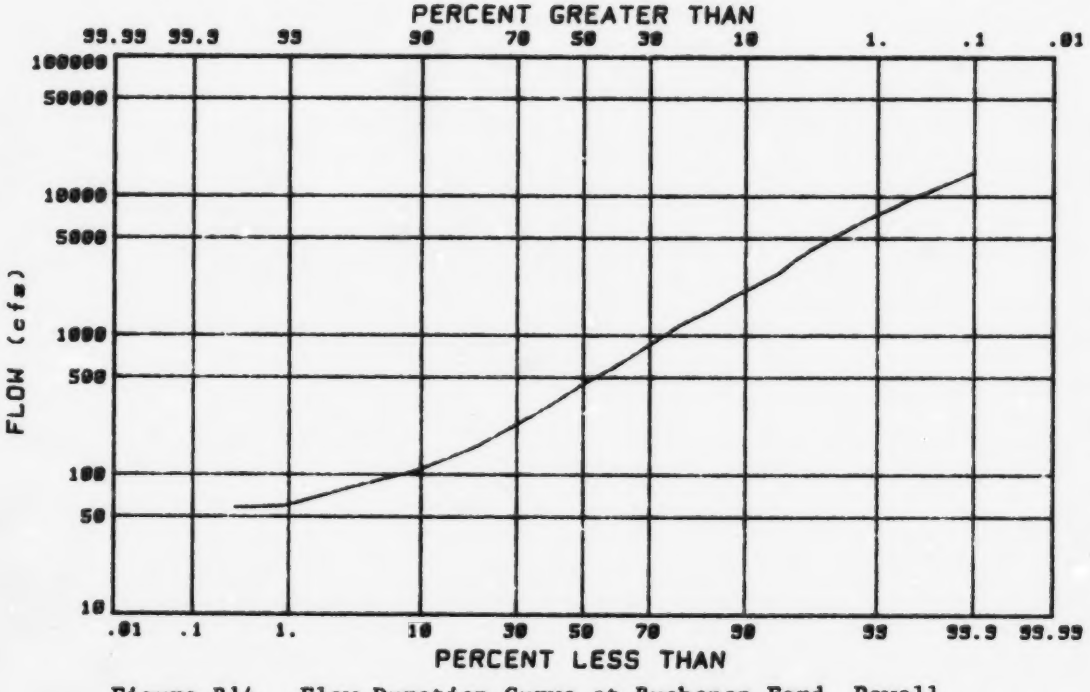

Figure B14. Flow Duration Curve at Buchanan Ford, Powell River Mile 99.2.

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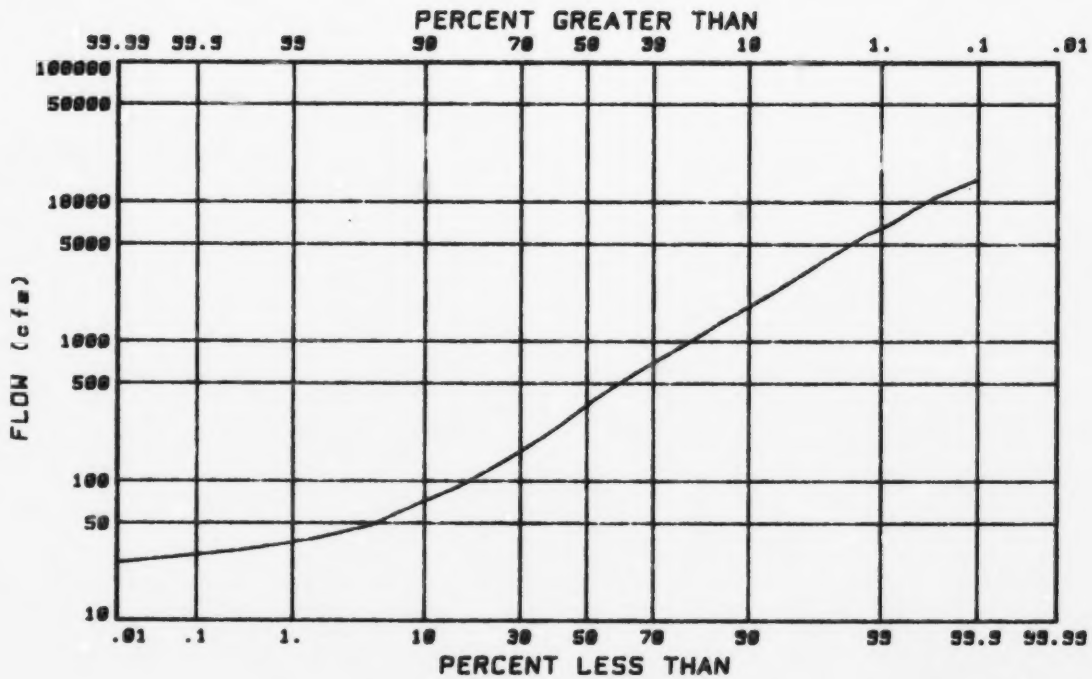

Figure B15. Flow Duration Curve at Fletcher Ford, Powell River Mile 117.4.

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APPENDIX C

SUSPENDED SEDIMENT MEASUREMENTS FOR TASK I STUDY REACHES

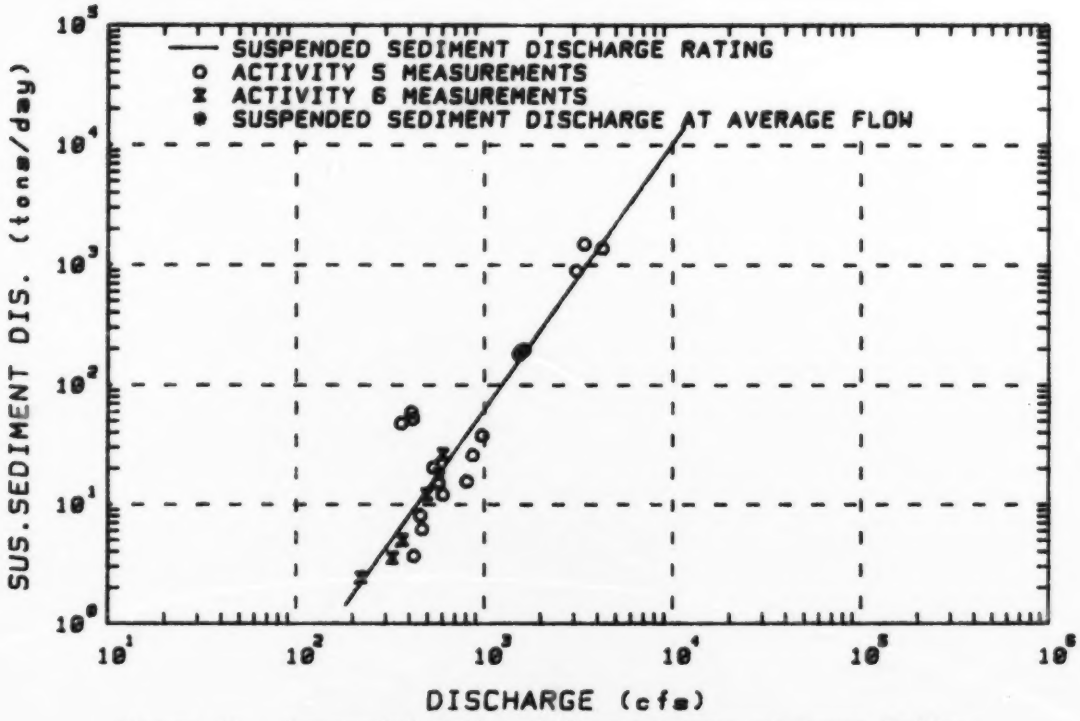

Figure C1. Suspended Sediment Measurements at Topsy Bridge, Buffalo River Mile 79.9.

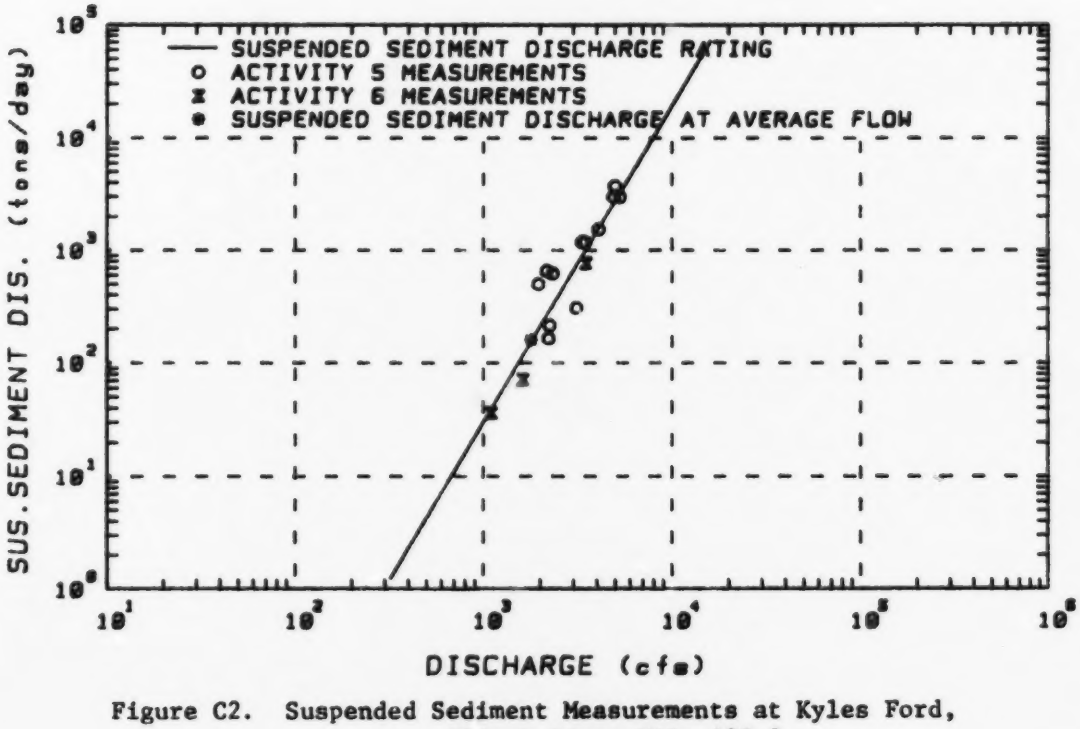

Figure C2. Suspended Sediment Measurements at Kyles Ford, Clinch River Mile 189.5.

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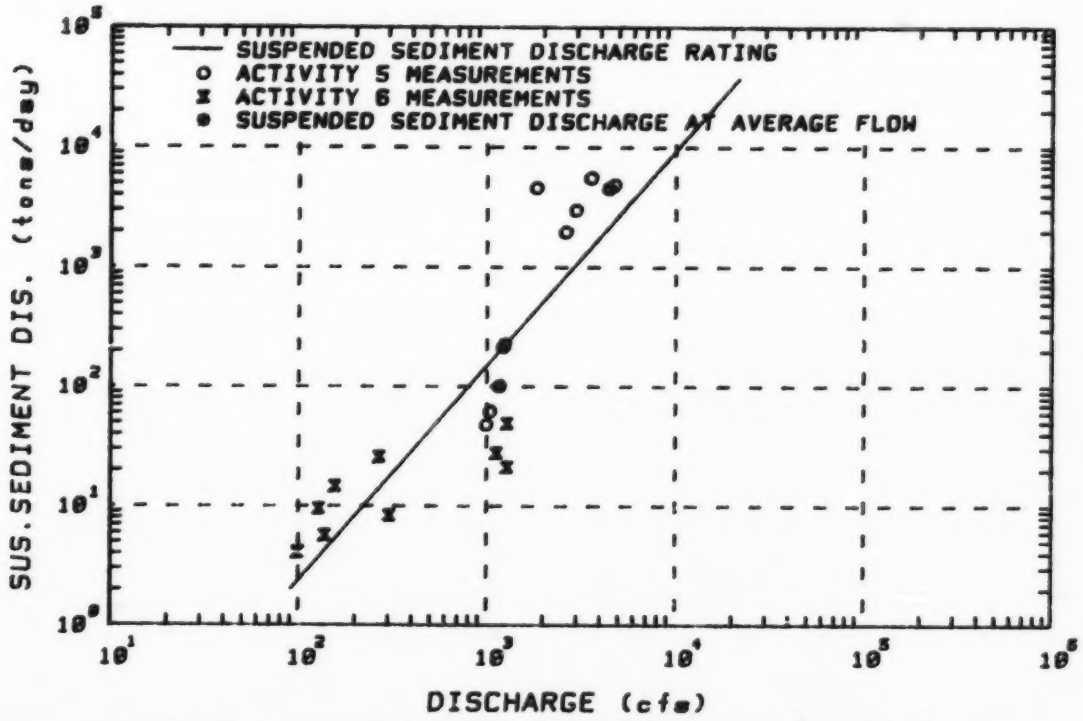

Figure C3. Suspended Sediment Measurements at Fort Blackmore, Clinch River Mile 227.4.

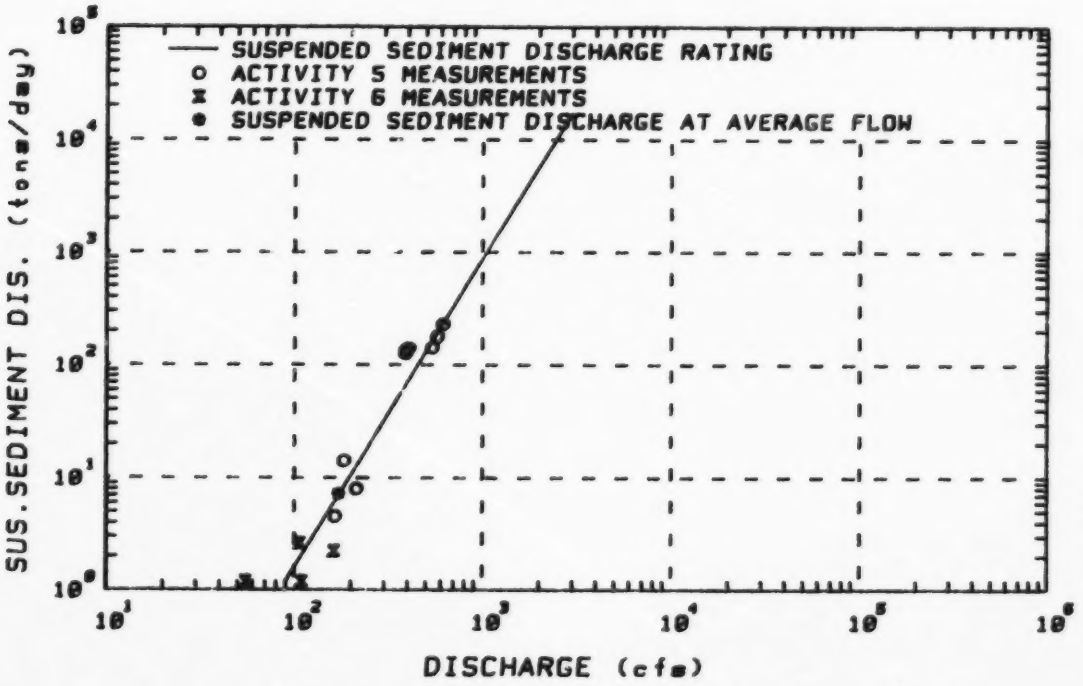

Figure C4. Suspended Sediment Measurements at Copper Creek Mile 1.9.

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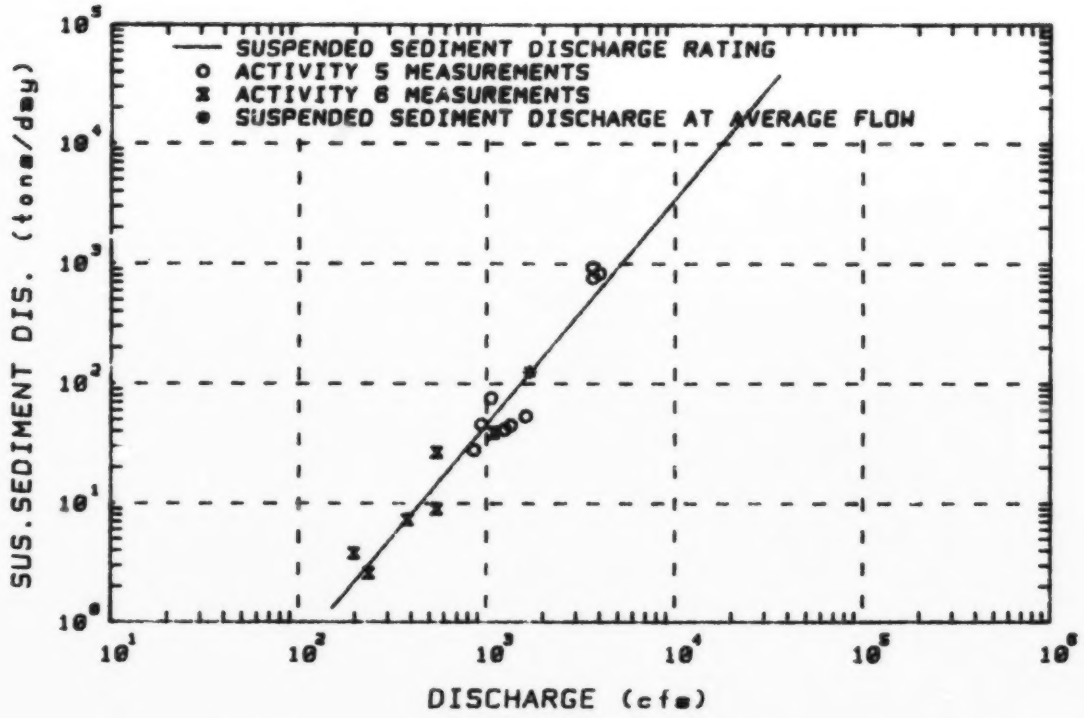

Figure C5. Suspended Sediment Measurements at Sowell Ford, Duck River Mile 159.4.

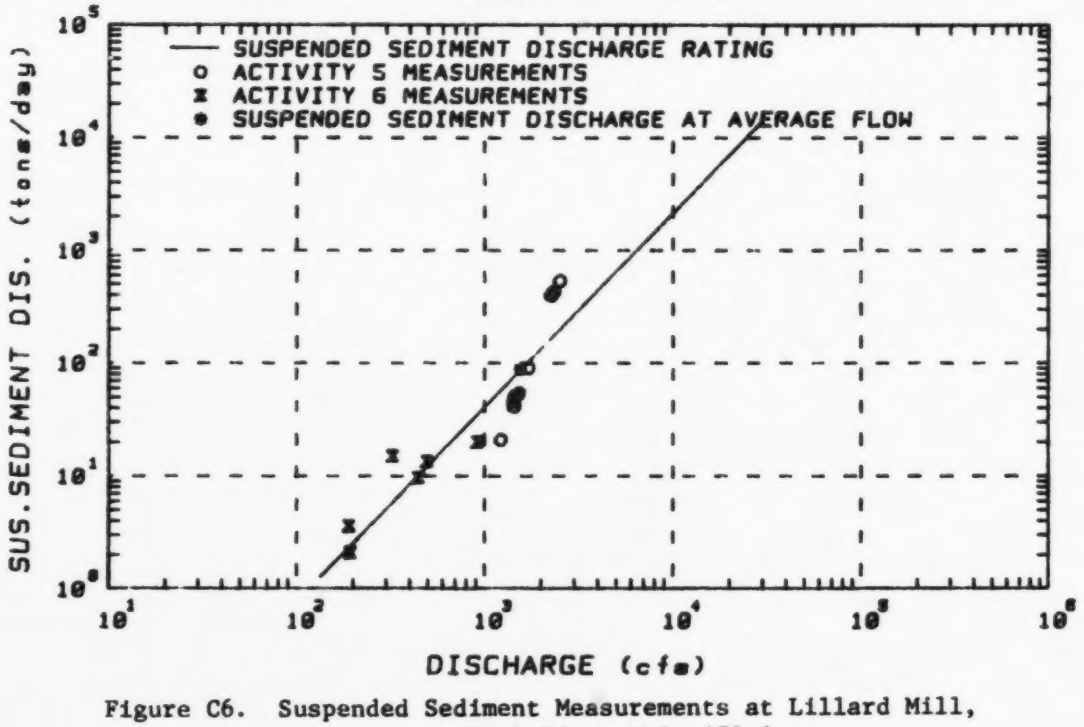

Figure C6. Suspended Sediment Measurements at Lillard Mill, Duck River Mile 179.1.

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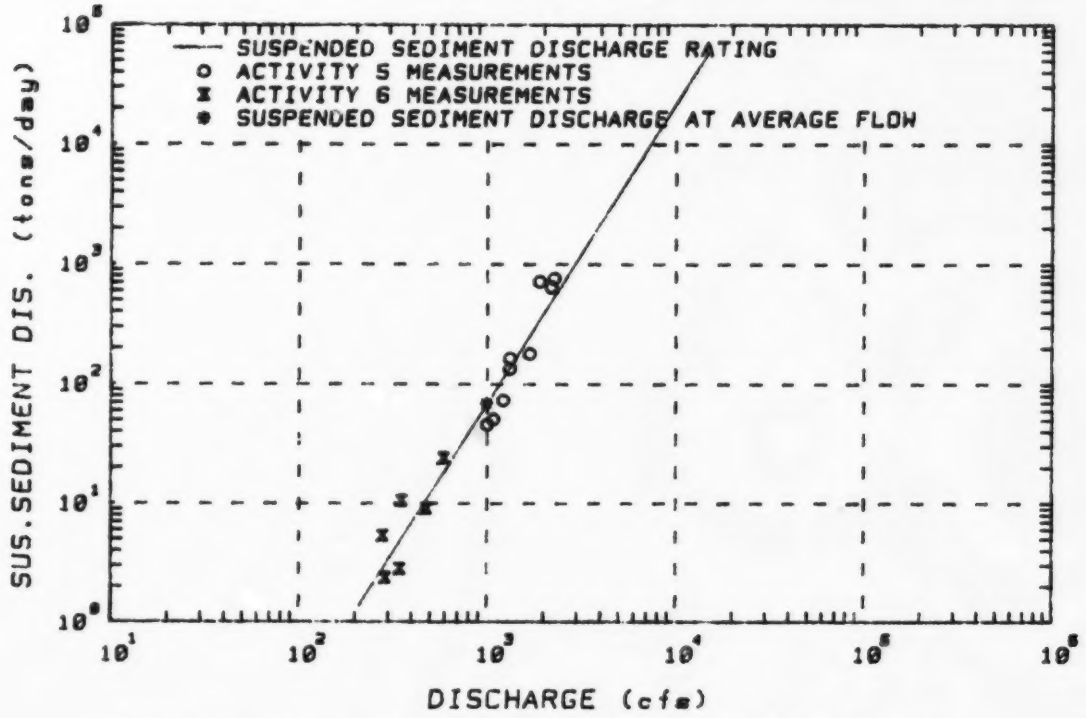

Figure C7. Suspended Sediment Measurements at Halls Mill, Duck River Mile 202.2.

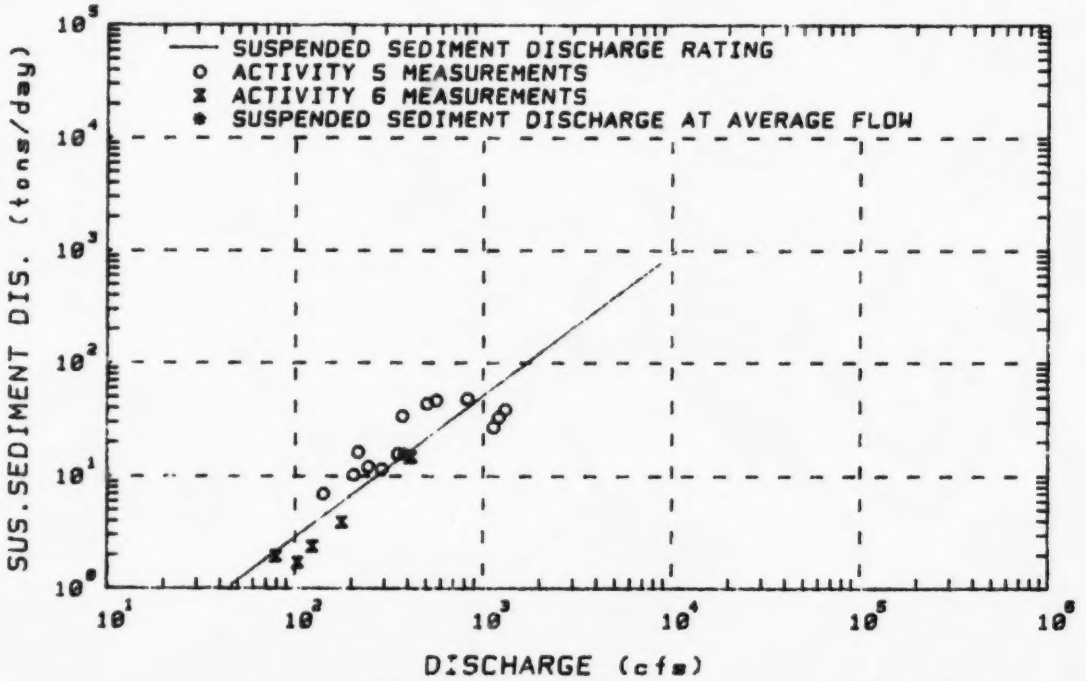

Figure C8. Suspended Sediment Measurements at Dement Bridge, Duck River Mile 243.1.

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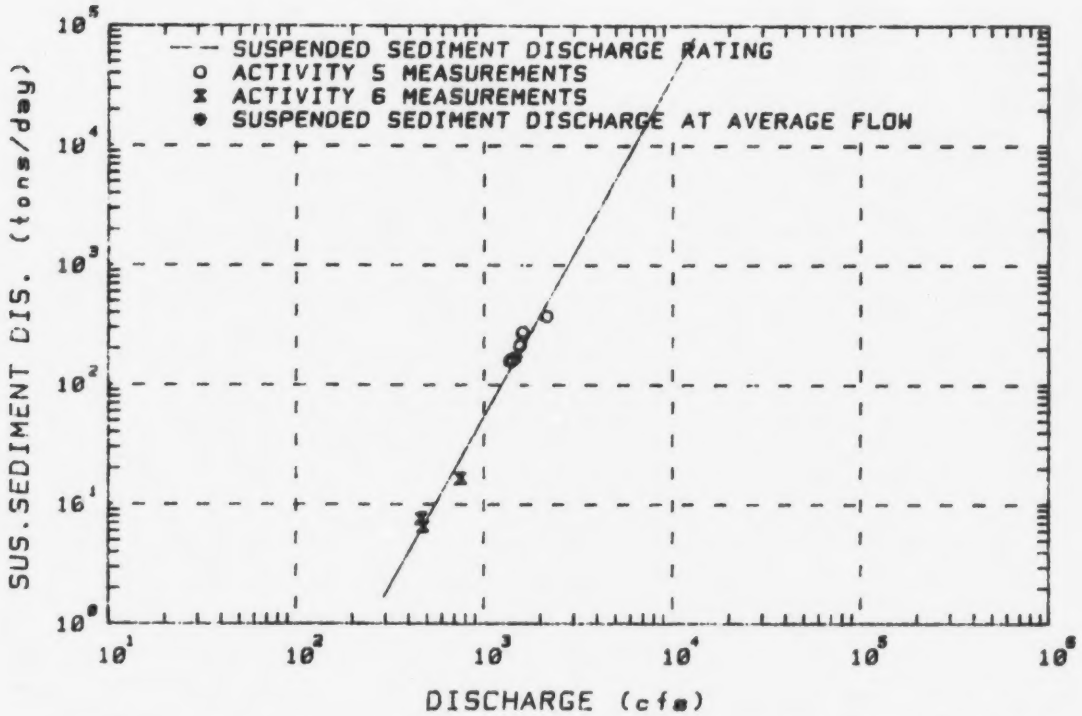

Figure C9. Suspended Sediment Measurements at Elk River Mile 91.4.

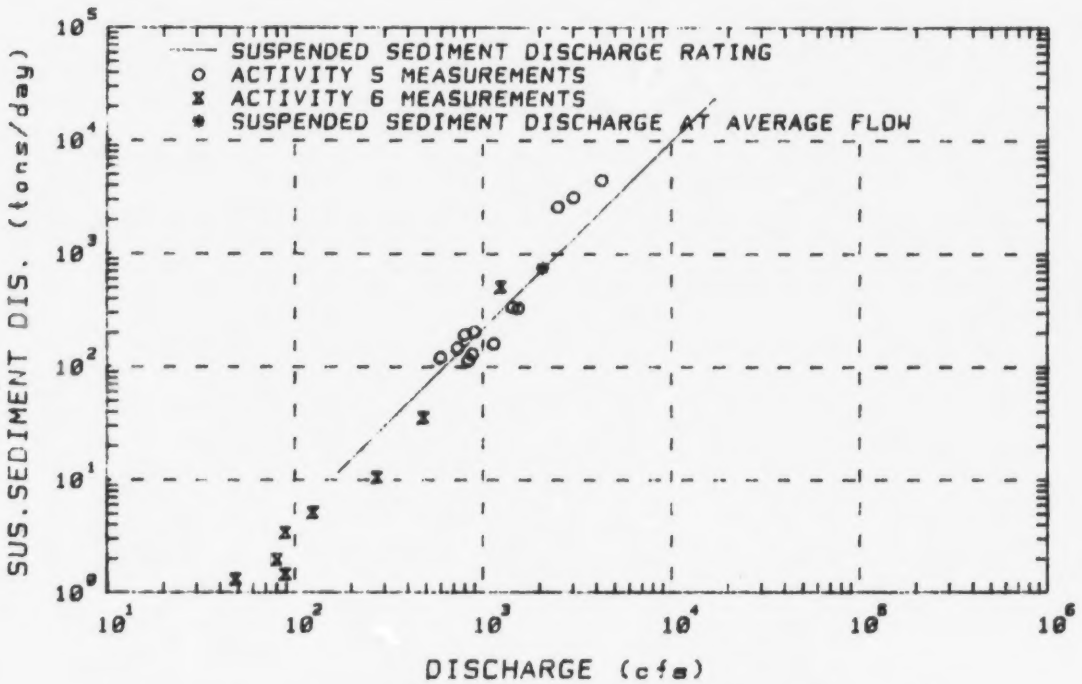

Figure C10. Suspended Sediment Measurements at Hale Bridge, Nolichucky River Mile 27.8.

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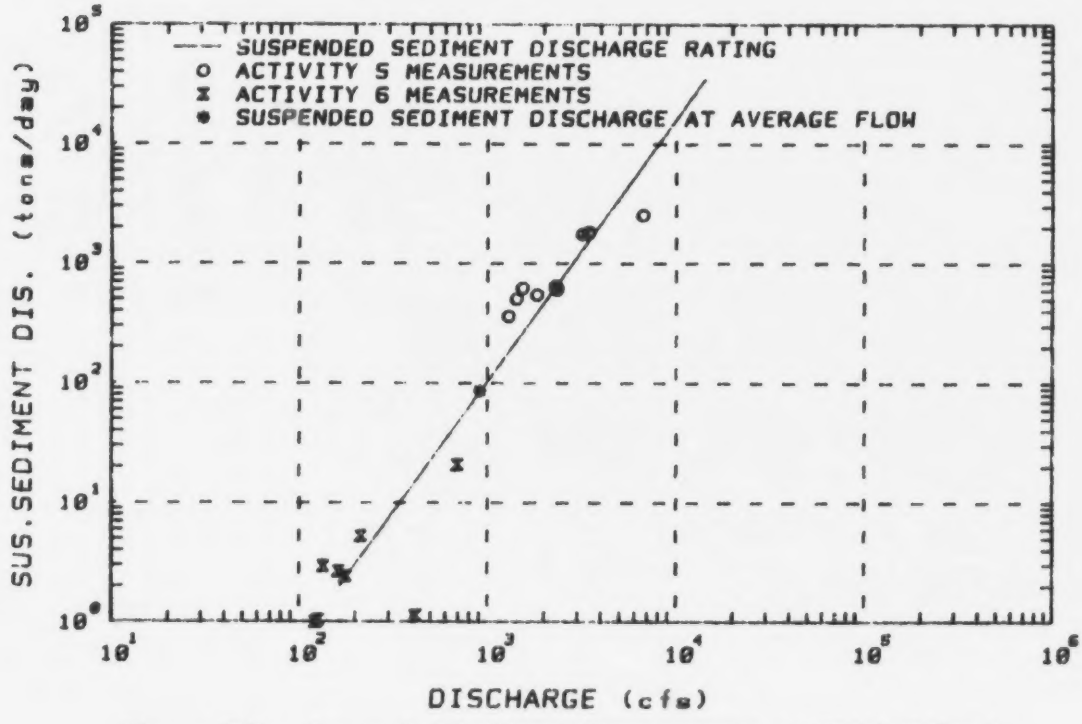

Figure C11. Suspended Sediment Measurements at Click Island, North Fork Holston River Mile 6.2.

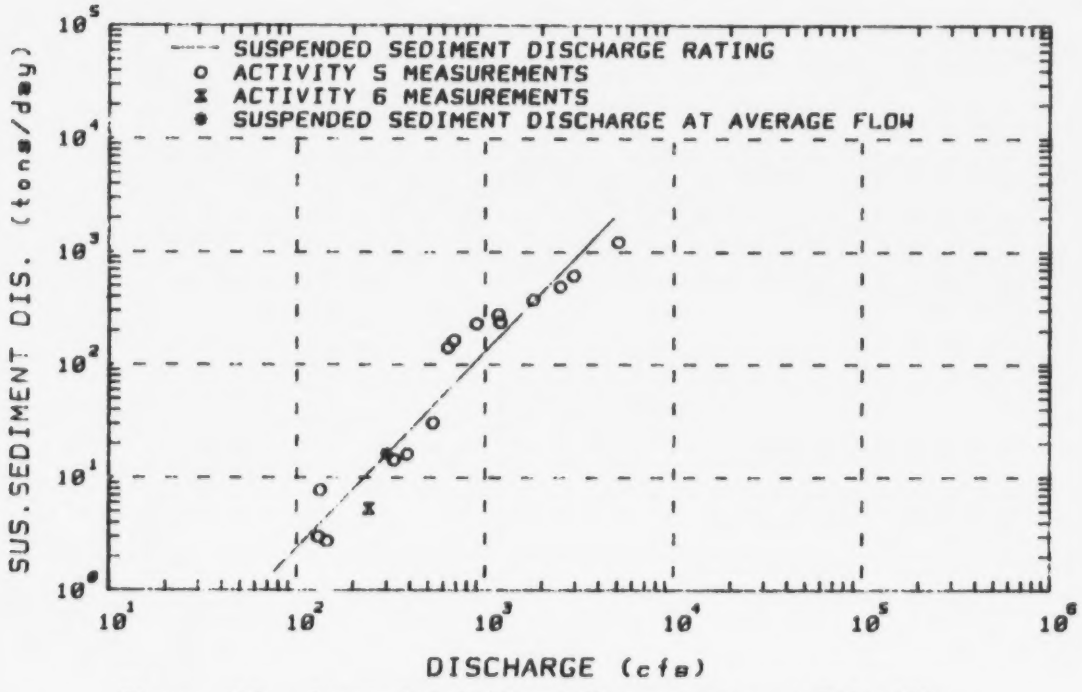

Figure C12. Suspended Sediment Measurements at Saltville, North Fork Holston River Mile 85.2.

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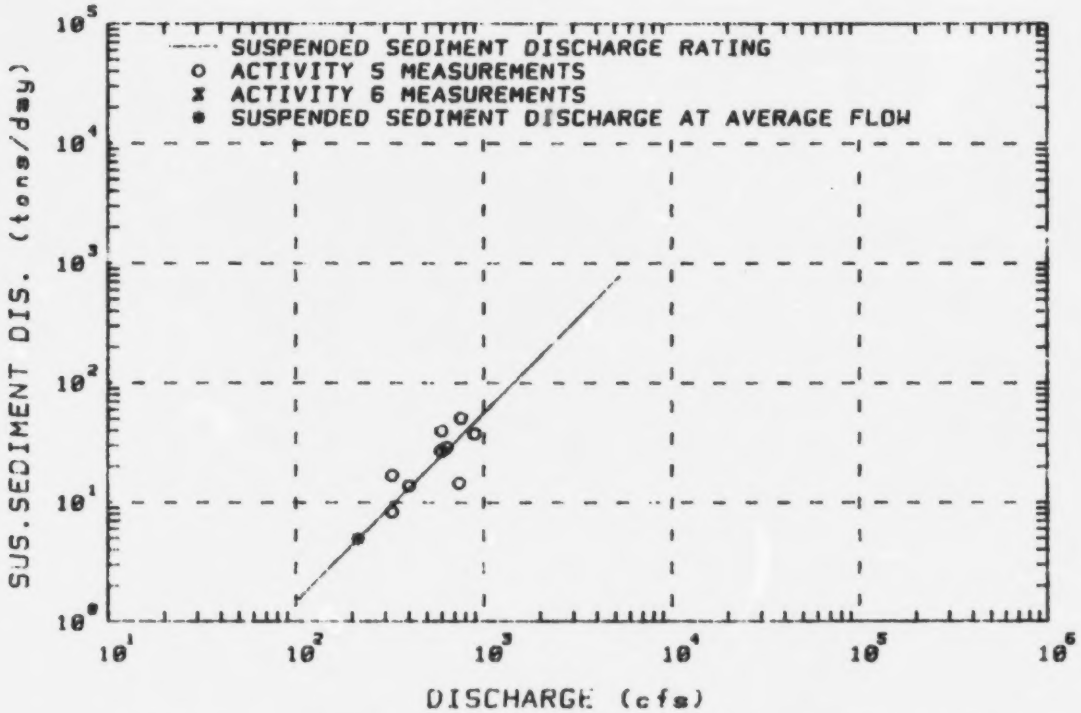

Figure C13. Suspended Sediment Measurements at Estill Fork, Paint Rock River Mile 60.0.

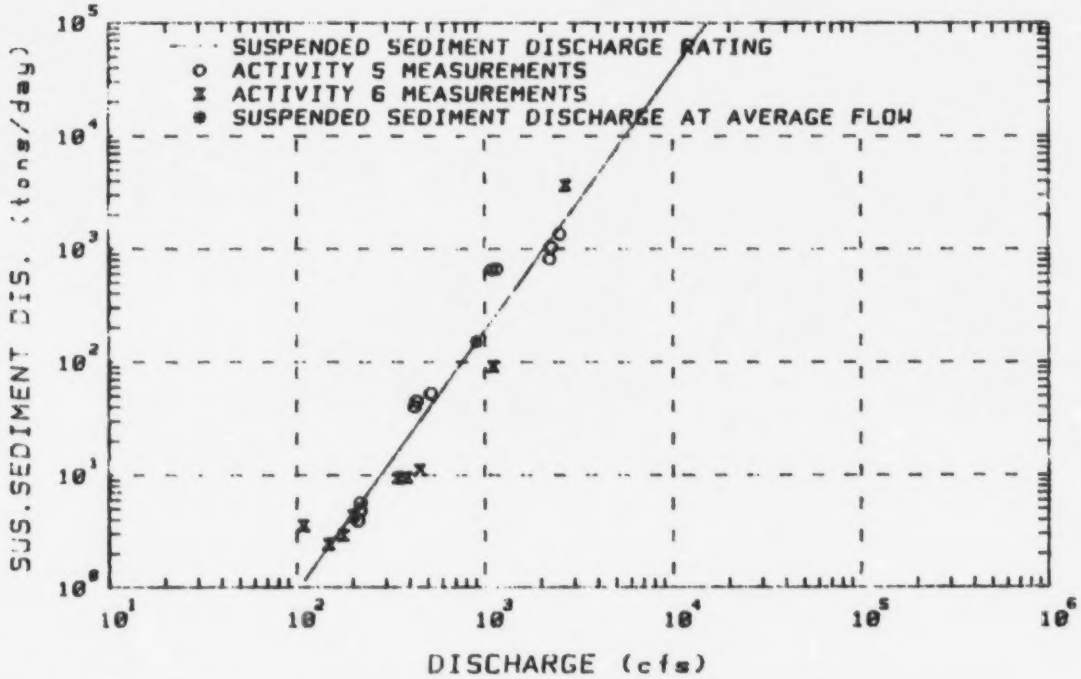

Figure C14. Suspended Sediment Measurements at Buchanan Ford, Powell River Mile 99.2.

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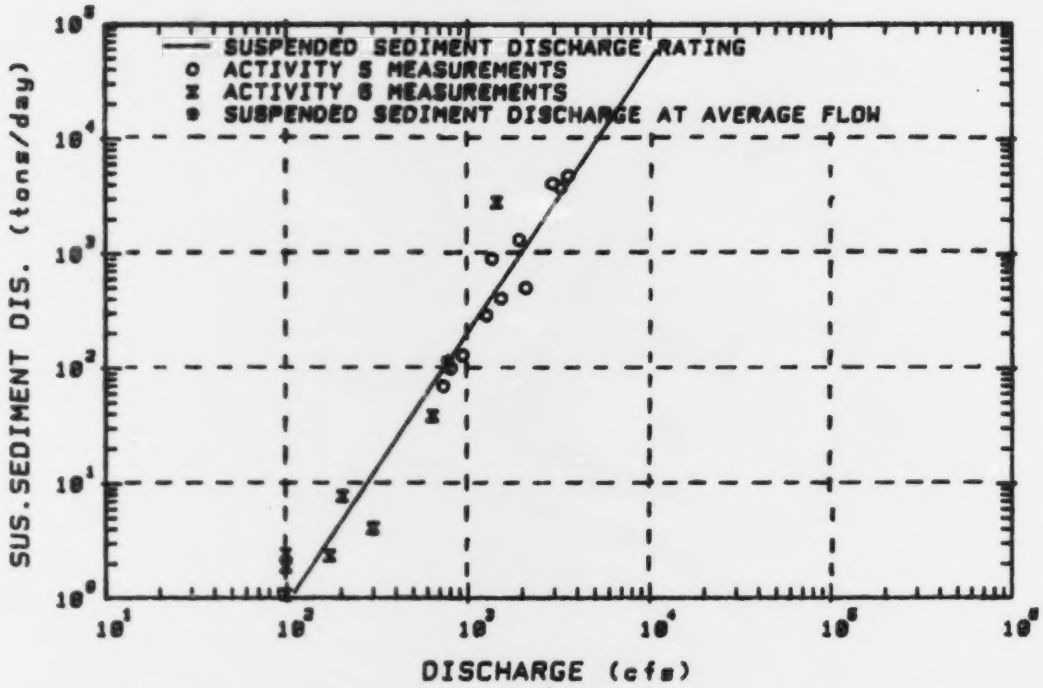

Figure C15. Suspended Sediment Measurements at Fletcher Ford, Powell River Mile 117.4.

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